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ANPP CORROSION PROGRAM

Loop Testing of Inconel, Nickel, Monel and Bimetal Heat Exchangers

MND-E-2681

December 1961

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FOREWORD

This report was prepared by the Nuclear Division of the Martin Marietta Corporation for submission to the Nuclear Power Field Office, Engineer Research and Development Laboratories, U. S. Army Corps of Engineers.

The report was prepared under Contract DA-44-009-Eng-3581 and describes the loop testing of 12 corrosion vessels.

CONTENTS

		Page
	Legal Notice	ii
	Distribution List	iii
	Foreword	vii
	Contents	ix
	Summary	xi
I.	Introduction	1
II.	Fabrication of Test Heat Exchanger	5
III.	Test Facility Description	9
	A. Primary System	9
	B. Model Secondary System	13
	C. Miniature Secondary System	15
IV.	Test Operations	19
	A. Preparation for Tests	19
	B. Test Conditions	20
	C. Water Environment Control	23
	D. Accumulation of Test Time	24
V.	Environmental Chemistry	27
	A. MIN 10 and MIN 11	28
	B. MIN 13 and MIN 14	28
	C. MIN 15 and MIN 16	29
	D. MIN 18 and MIN 19	29
	E. MOD SG-4 and MOD SH-4--Bimetal	30

CONTENTS (continued)

		Page
	F. MOD SG-7 and MOD SH-8--Inconel	30
VI.	Heat Transfer Index	31
VII.	Test Results	35
	A. MIN-10--Inconel	35
	B. MIN-11--Inconel	39
	C. MIN-13--Monel	39
	D. MIN-14--Monel	44
	E. MIN-15--Bimetal	44
	F. MIN-16--Bimetal	48
	G. MIN-18--Nickel	54
	H. MIN-19--Nickel	54
	I. Bimetal Steam Generator--SG-4	58
	J. Bimetal Superheater--SH-4	62
	K. Inconel Steam Generator--SG-7	62
	L. Inconel Superheater--SH-7	66
VIII.	Conclusions	69
IX.	References	71
	Appendix A--Calendar of Loop Testing	73

SUMMARY

This report describes corrosion tests, performed under the Martin-ANPP Corrosion Program, on 12 test vessels. Two sets of model heat exchangers (a set consists of a steam generator and superheater) and eight miniature heat exchangers were tested dynamically in a pressurized water loop. One set of model heat exchangers had bimetal tubes (stainless steel in the primary, carbon steel in the secondary) and the other had Inconel tubes. The set with bimetal tubes was service tested for 4890 hours and that with Inconel tubes was service tested 4747 hours. The secondary environment in the bimetal vessels simulated the SM-1 water conditions while the secondary in the Inconel vessels simulated reactor quality water.

Two of the miniature heat exchangers, MIN 10 and 11, had Inconel tubes, MIN 13 and 14 had Monel tubes, MIN 15 and 16 had bimetal tubes and nickel tubes were used in MIN 18 and 19. The test durations for the miniature heat exchangers, MIN 10, 11, 13, 14, 15, 16, 18 and 19, were 3045, 3024, 1393, 1418, 3015, 3035, 1385 and 1350 hours, respectively.

The Inconel, nickel and Monel tubing performed well in both reactor grade and high chloride secondary water. Pitting occurred in all three metals but was less prevalent in the Inconel tubing. The Inconel tubing in the model vessels exposed to reactor grade water did not pit.

The bimetal model vessels, which were tested using reactor grade water, performed far better than similar vessels exposed previously to a high chloride secondary environment. Nevertheless, the degree of pitting which occurred was prohibitive for long-life steam generators.

Tubing in one of the bimetal miniature vessels was defected to expose stainless steel to the high chloride secondary environment. The hypothesis, that the carbon steel provides cathodic protection and prevents stress corrosion cracking of the stainless steel, was supported by the test results; no cracking of the stainless sublayer occurred. However, complete substantiation should be based on further tests.

I. INTRODUCTION

This report describes the loop testing and subsequent evaluation of 12 corrosion test vessels. This work was performed under the Martin-ANPP Corrosion Program.

The objectives of this program were to determine the applicability of various metals for use in heat exchanger fabrication and to investigate the type and extent of corrosion in specified environments. Specifically, this included:

(1) The determination of the effects of secondary water conditions on heat exchanger life, using various exchanger materials. The most severe single water condition was limited to 1000-ppm chloride with air-saturated water and air as a cover gas.

(2) The examination of the techniques used in test heat exchanger fabrication.

(3) The recommendation of materials and service conditions for operating heat exchangers.

The general procedure for meeting these objectives was evolved into the following:

(1) A broad range of water conditions for a particular material was investigated in rocking autoclave tests. A more definitive range of water conditions was then selected on the basis of autoclave test results, e.g., satisfactory or unsatisfactory.

(2) Miniature heat exchangers (MIN X), of the general configuration shown in Fig. 1, were tested to verify the autoclave results. On this basis, the range of water conditions of interest was narrowed further.

(3) Specific water conditions, based on the results of Steps (1) and (2), were then selected for use in the testing of model heat exchangers (Mod SG-X or SH-X) of the general configuration shown in Fig. 2.

The results of previous autoclave studies conducted under this program are reported in Refs. 1, 2, 3 and 4. Of particular interest are the studies described in Ref. 4 which covers the autoclave tests

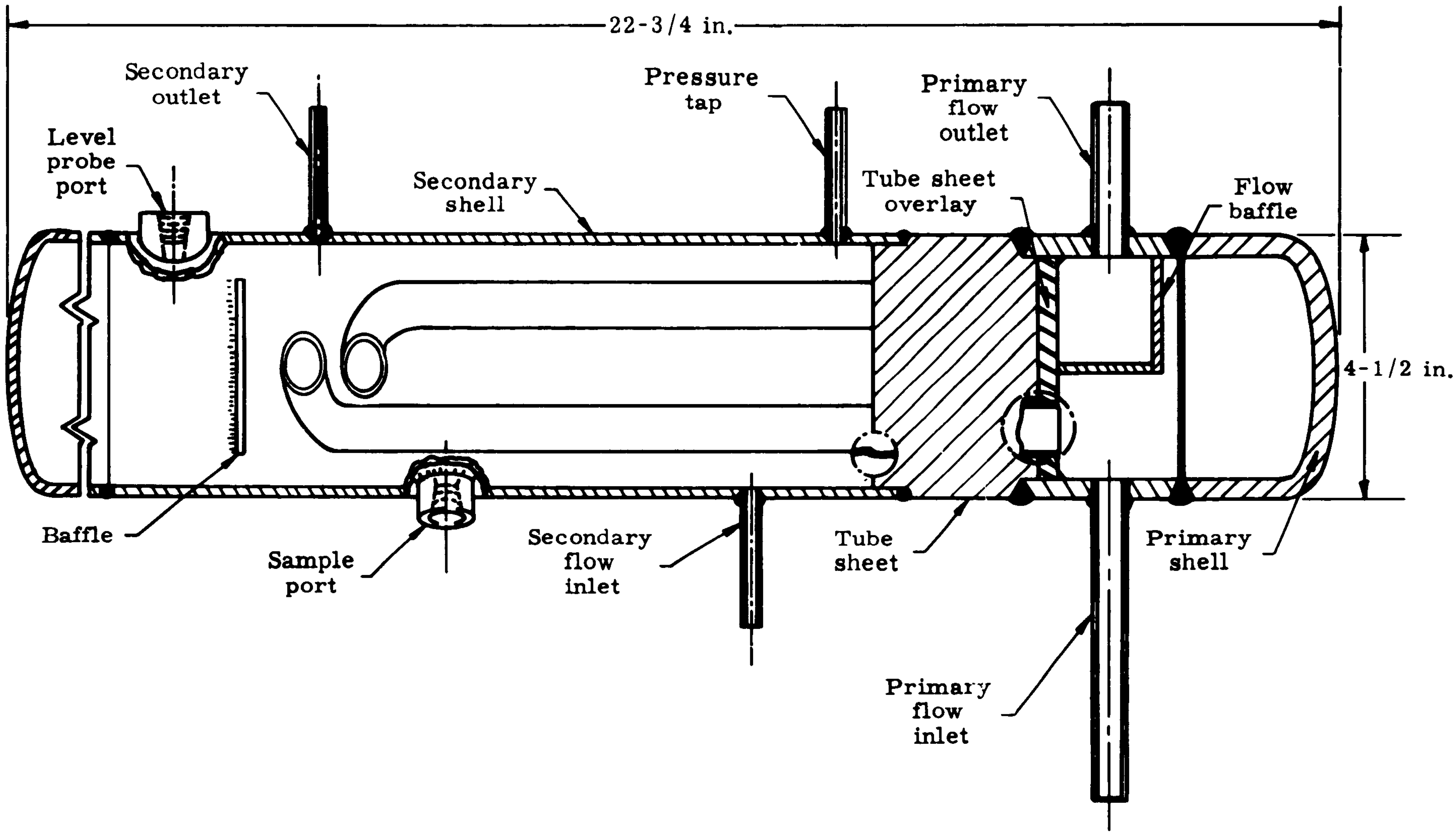


Fig. 1. Miniature Heat Exchanger Design

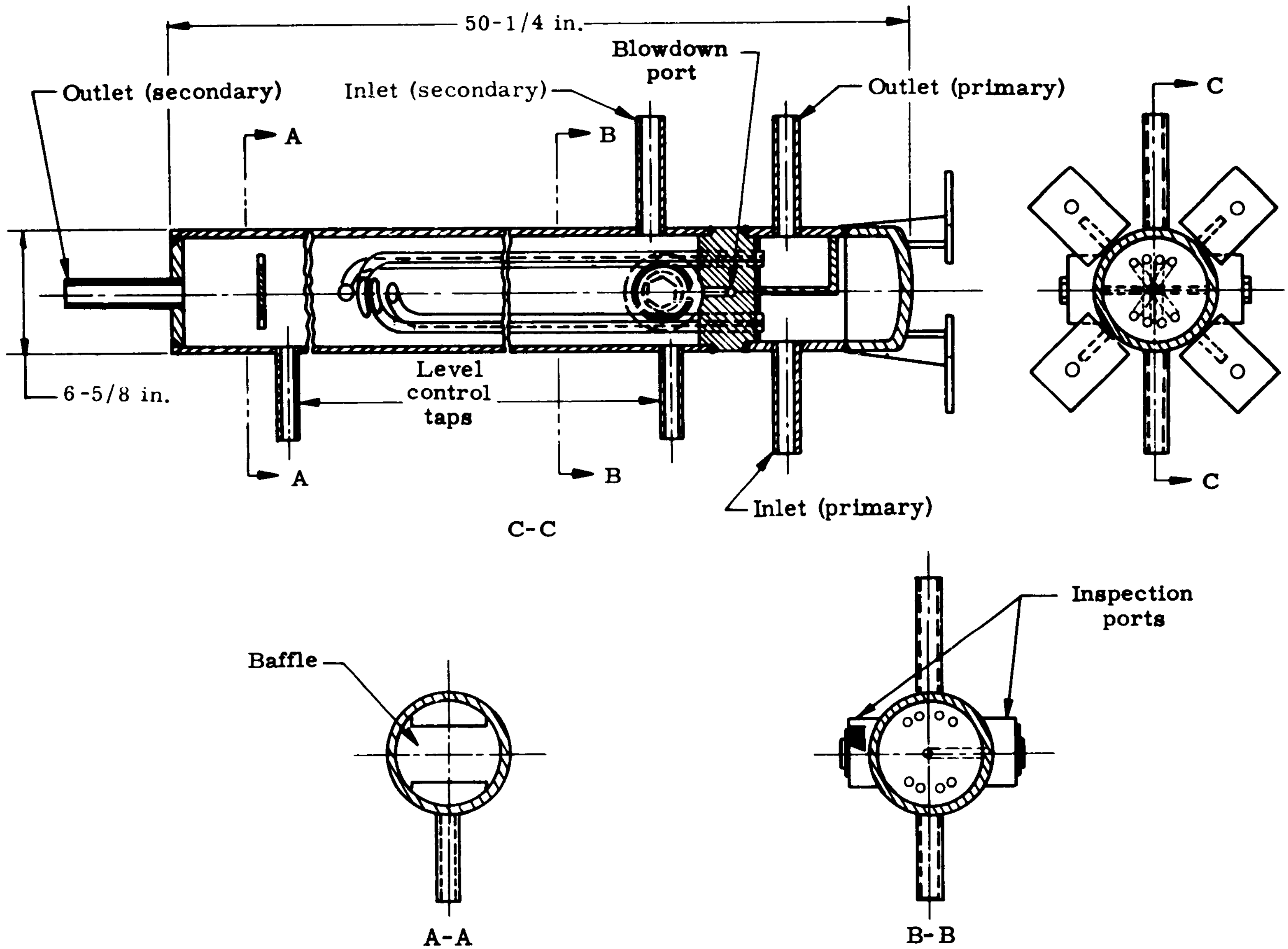


Fig. 2. Model Heat Exchanger Design

on Monel, nickel and Inconel which figure prominently in the current tests. Dynamic loop tests which have been conducted under the program are described in Refs. 5, 6 and 7. Many of the methods and procedures employed in the program, which are independent of the particular heat exchanger being studied, are described in detail in Ref. 8. This reference is cited a number of times in the text and should be consulted if a detailed description of a particular point or procedure is desired.

II. FABRICATION OF TEST HEAT EXCHANGERS

Heat exchangers fabricated and tested during this phase of the program were of two general types: miniature heat exchangers of the type shown in Fig. 1 and designated MIN X and model heat exchangers of the type shown in Fig. 2. Model vessels were tested in sets, each of which consisted of a steam generator, MOD SG-X, and a superheater, MOD SH-X. Figure 2 shows a steam generator. The superheater design is identical except for the absence of inspection ports and the incorporation of a flow baffle around the tubes to increase the steam velocity. Details of vessel fabrication procedures are given in Ref. 8.

The model vessel illustrated in Fig. 2 contains four hairpin tubes of one-half inch outside diameter. This is characteristic, for example, of the Inconel vessels, MOD SG-7 and SH-7. Other vessels, e.g., the bimetal vessels, MOD SG-4 and SH-4, incorporated three tubes of three-quarter inch outside diameter. The choice depended on the size of tubing readily available in the specified material.

Table 1 lists the materials used in the fabrication of the test heat exchangers covered in this report.

The analysis of the tube material used to fabricate the test vessels is presented in Table 2.

In fabricating steam generators for reactor plant use, it is standard procedure to roll and seal weld tubes into the tube sheet. To investigate the need for the rolling operation, several vessels (MIN 10 and 11) were fabricated with one rolled and one unrolled tube. The results of these tests are discussed in Chapter VII.

Miniature vessels, MIN 15 and 16, and model vessels, MOD SG-4 and SH-4, were fabricated using bimetal tubing, i.e., carbon steel on the secondary side and stainless steel on the primary side. This type of tubing was used in the original steam generator for the SM-1 plant. In previous tests on vessels employing this type of tubing (Ref. 6) severe corrosion and pitting of the carbon steel had exposed relatively large areas of stainless steel to the high chloride secondary environment. Although stainless steel is normally susceptible to stress corrosion cracking under these circumstances, no cracking occurred. It was suggested that the carbon steel provided cathodic protection, effectively preventing cracking of the stainless steel. To further investigate this possibility, the tubing in MIN 16 was purposely defected during the fabrication process to expose the stainless steel sublayer to the high chloride secondary environment. Defects were made in tubing which was exposed in the liquid and vapor phases and at the interface; these are illustrated in Fig. 3. Results of this investigation are also discussed in Chapter VII.

TABLE 1

Materials of Fabrication; Secondary Surfaces

Test Vessel	Tubes	Tube Sheet	Tube Sheet Clad	Tube-to-Tube Sheet Weld	Secondary Shell
Inconel					
MIN 10 and 11	Inconel	Inconel	None	Fused junction	1030 carbon steel
SX-7	Inconel	1030 carbon steel	Inco-weld A	Fused junction	1030 carbon steel
Bimetal					
MIN 15 and 16	Bimetal*	1020 carbon steel	Type 308 SS	Type 308 SS weld rod	1030 carbon steel
SX-4	Bimetal*	Carbon steel	Type 308 SS	Type 308 SS weld rod	Carbon steel
Monel					
MIN 13 and 14	Monel	1020 carbon steel	Nickel	Fused junction	1030 carbon steel
Nickel					
MIN 18 and 19	Nickel	1020 carbon steel	Nickel	Fused junction	1030 carbon steel

*Primary side AISI Type 304 SS, 0.032 inch thick; secondary side 1020 carbon steel, 0.032 inch thick.

TABLE 2

Chemical Composition of Tube Materials

Heat Exchanger	Material	Composition (%)									
		Ni	Cr	Mn	Si	Cu	Fe	C	Ti	P	S
SX-7	Inconel	75.6	15.6	0.15	0.16	0.04	7.12	0.03	--	--	--
SX-4	1020 CS*	--	--	0.45	--	--	rem	0.20	--	0.04 max	0.05 max
MIN 10 and 11	Inconel	75.4	15.3	0.23	0.20	0.07	8.4	0.04	2.6	--	--
MIN 13 and 14	Monel	65.0	--	0.95	0.16	32.65	1.11	0.12	--	--	--
MIN 15 and 16	1020 CS*	--	--	0.45	--	--	rem	0.20	--	0.04 max	0.05 max
MIN 18 and 19	Nickel A	99.50	--	0.28	0.04	0.02	0.07	0.09	--	--	--

*Nominal composition.

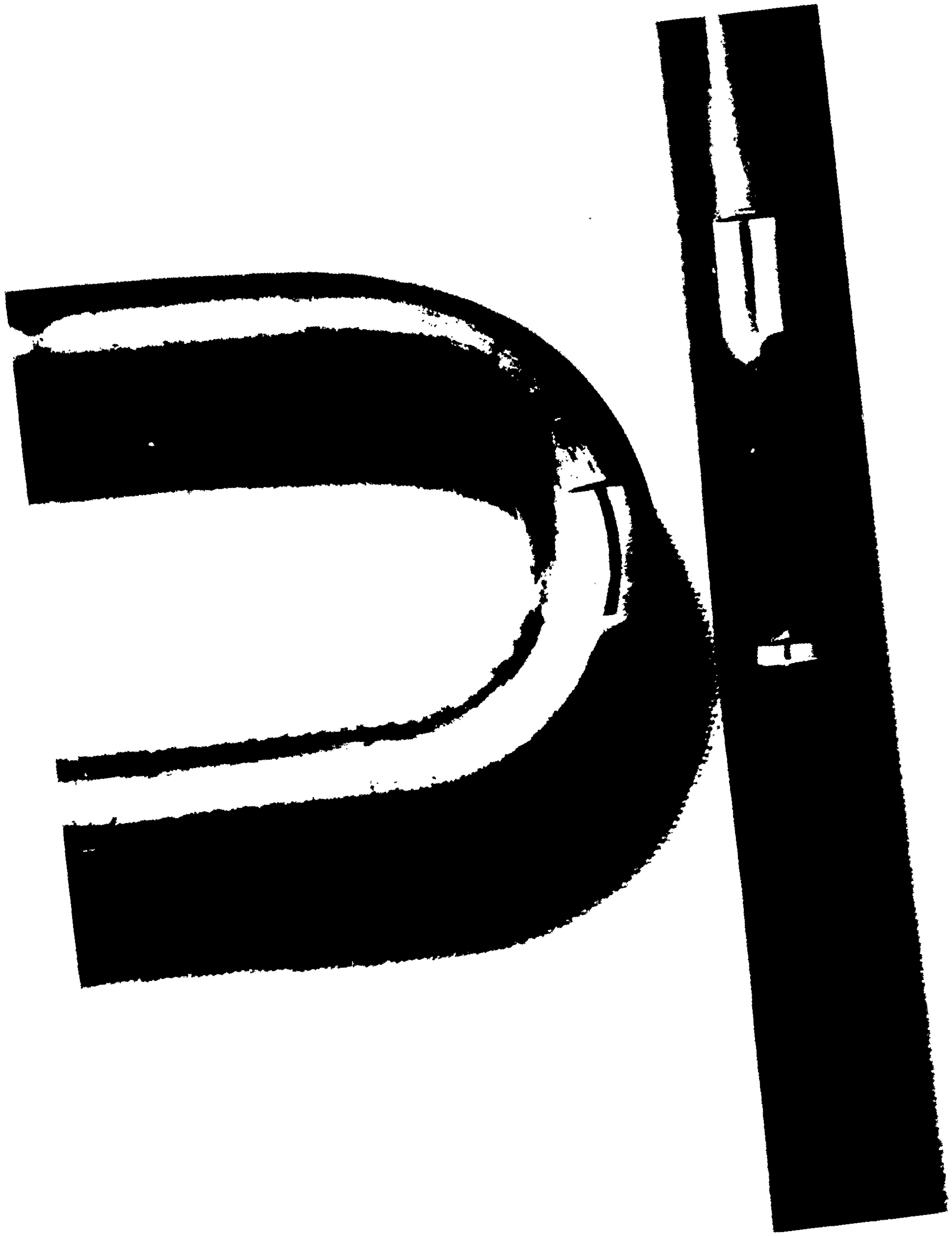


Fig. 3. Bimetal Tubing for MIN 16 Showing Defects and Exposed Stainless Steel

III. TEST FACILITY DESCRIPTION

The corrosion test facility is designed to perform continuous long-term tests on model and miniature heat exchangers of the types shown in Figs. 1 and 2. Operating temperatures and pressures simulating typical pressurized water reactor conditions can be maintained. Two sets of model vessels (a set consists of a steam generator and a superheater in series) and four miniature vessels can be accommodated simultaneously.

The facility consists of a primary system which furnishes heat for all of the test vessels. Each set of model vessels has an individual secondary system while a third secondary system serves the four miniature vessels in a parallel flow arrangement. The facility control system requires manual startup operations, but thereafter all test parameters are maintained by automatic controls. Safety interlocks provide for automatic shutdown in the event of a malfunction.

Figure 4 shows a photograph of the entire facility except for the control panels which are located in an adjacent control room. These are shown in Fig. 5. The following descriptions of the primary and secondary systems are simplified and include only the basic flow schematic and equipment. A detailed description may be found in Ref. 8.

A. PRIMARY SYSTEM

A simplified flow schematic of the primary system is shown in Fig. 6. The system is, for the most part, welded or flanged construction using 300 series stainless steel. Some stainless steel tubing, connected by threaded fittings, is used in the demineralizer subsystem. The test vessels are an integral part of the loop but flanged and threaded connections permit easy replacement of any vessel.

Referring to Fig. 6, water discharged from the circulating pump (1) passes through three line heaters (2) (3) (4) containing immersion heaters. The first two of these (2) (3) are on manual on-off control and the third (4) is regulated by a saturable reactor control (5) which responds to the temperature of a thermocouple (6) upstream of the test vessels to maintain the desired test parameter. Flow from the line heaters may be directed, as desired, through five parallel subsystems (A) (B) (C) (D) (E) across the circulating pump.

The demineralizer subsystem (A) is used to maintain the desired water purity and receives a portion of the total circulating pump output. The water passes through an economizer (7) and a plant water

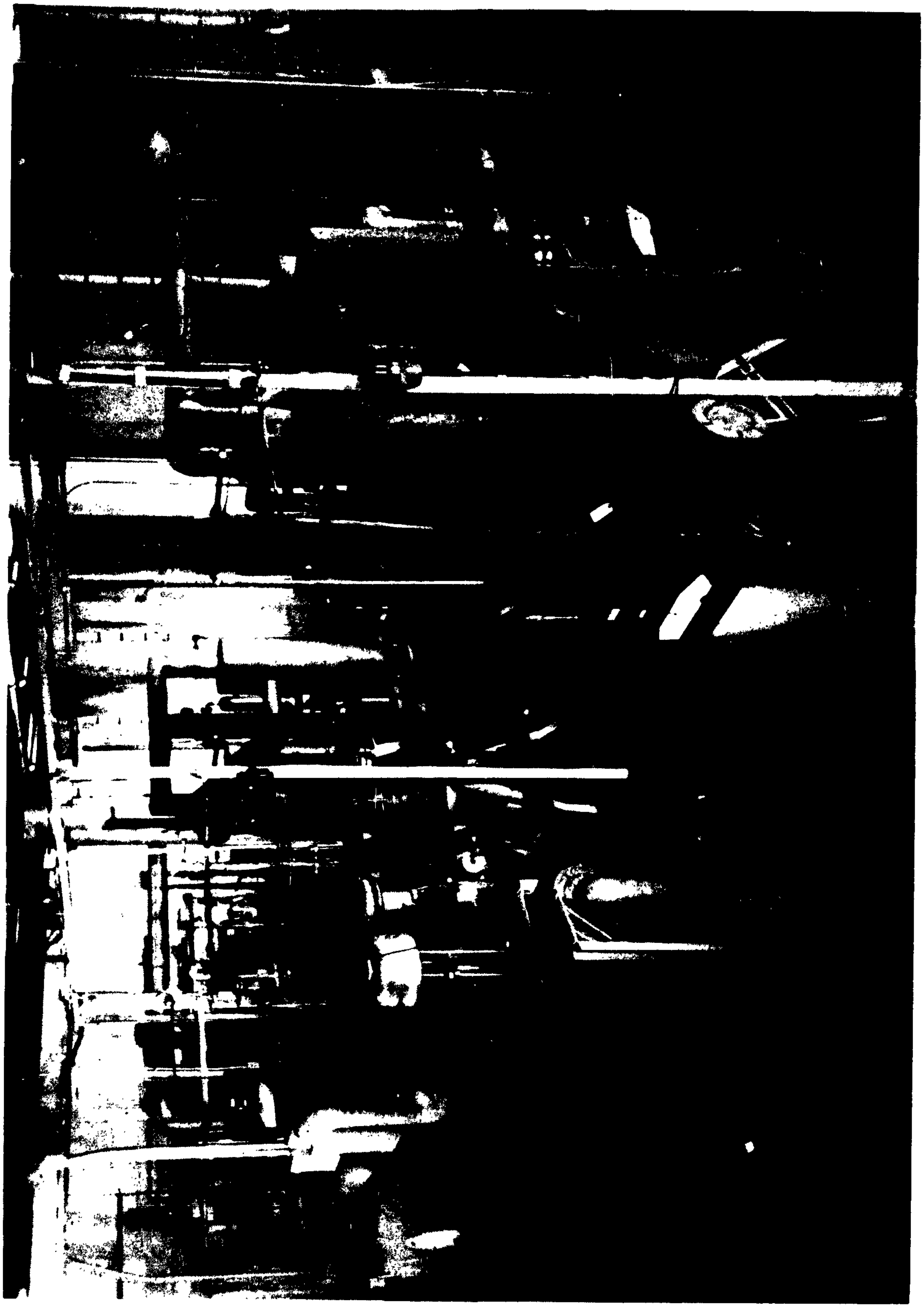


Fig. 4. Martin-ANPP Corrosion Loop (Photo No. 8B-33267)

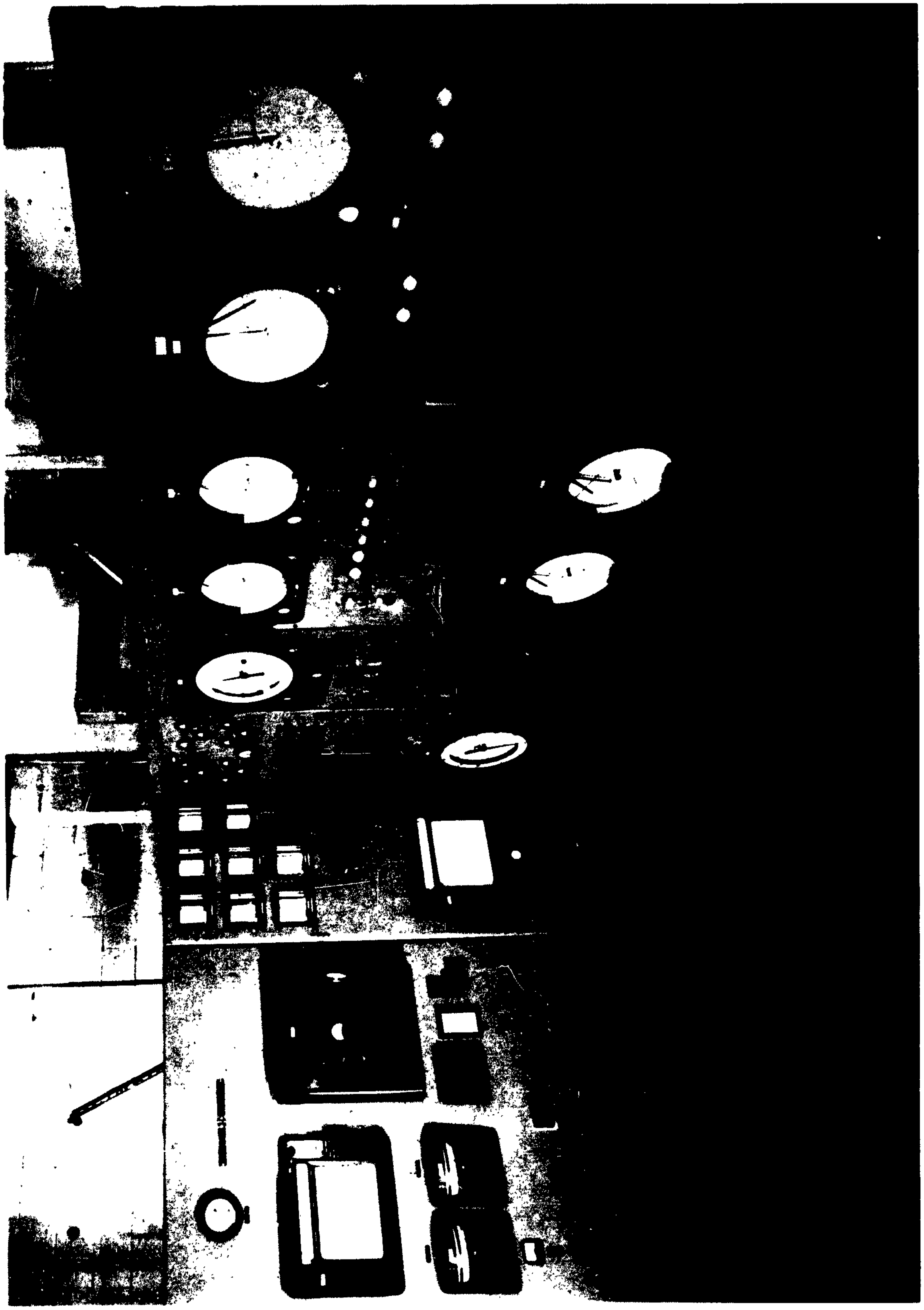


Fig. 5. Corrosion Loop Control Panel (Photo No. 8B-33264)

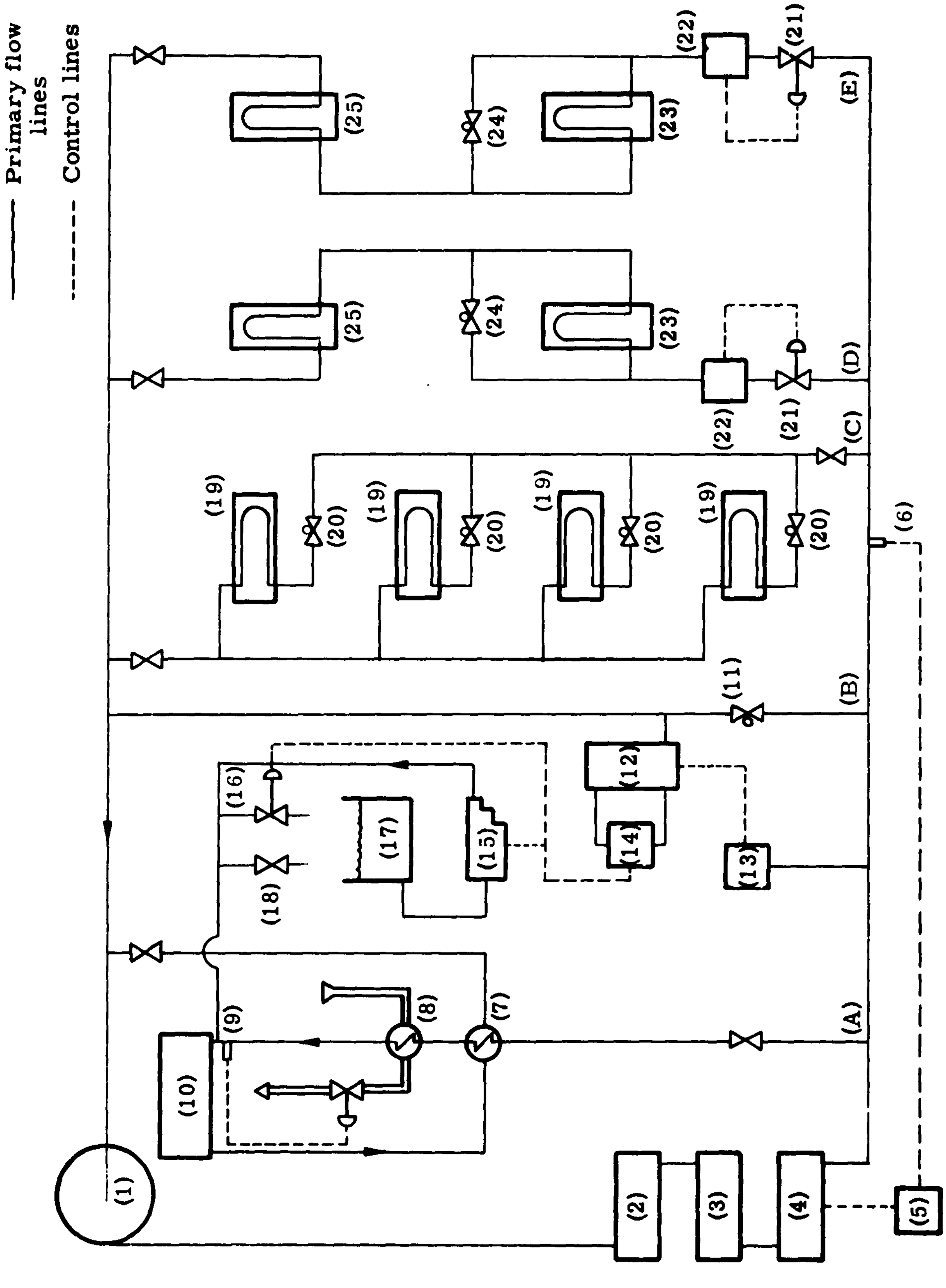


Fig. 6. Simplified Primary Flow Schematic

cooling coil (8) to reduce the water temperature at thermocouple (9) to $\sim 120°$ F, the maximum permissible resin temperature. Flow from the demineralizer (10) goes through the economizer and back to the suction side of the circulating pump.

The pressurizer subsystem (B) contains a throttle valve (11) so if the minimum pump discharge required through the line heaters exceeds the test vessel requirements it may be bypassed to the pump suction. The pressurizer (12) is a vertical vessel containing immersion heaters which generate a steam pressure head. These heaters are controlled by a saturable reactor (13) which responds to the loop pressure. A level controller (14) attached to the pressurizer maintains the steam-water interface at the proper level, actuating a makeup pump (15) if leakage has lowered the level and a dump valve (16) if the expansion resulting from an increase in temperature has caused the level to rise. The storage tank (17) has immersion heaters which maintain the makeup water in a deaerated condition and a manual dump valve (18) is provided for draining the system.

The miniature vessel subsystem (C) contains the four miniature heat exchangers (19) in a parallel flow arrangement. Each vessel has a throttle valve (20) so the primary flow through each vessel may be controlled to result in the desired secondary steaming rate.

The model vessel subsystems (D) and (E) are identical and each contains a superheater (23) and a steam generator (25), in series. The flow through the vessels is controlled by a control valve (21) which responds to a flow meter (22) in the line. A bypass containing a throttle valve (24) is provided around the superheater so both the steaming rate and the superheat may be controlled.

B. MODEL SECONDARY SYSTEM

The two model secondary systems are identical and provide separate dynamic conditions for each set of model vessels. The systems are constructed of 300 series stainless steel tubing connected by threaded fittings. Except for the line heaters and the steam separators which are carbon steel, the systems components are also made of stainless steel. A simplified flow schematic of one of these systems is shown in Fig. 7.

Water is drawn from the storage tank (1) by the constant volume circulating pump (2). The pump discharge goes through the line heater (3) where the desired feed water temperature is achieved and through the level control valve (4). The water then normally goes through a sight gage (5) and a check valve (6) and into the steam generator (7). When chemicals are to be added to the generator, the flow is diverted

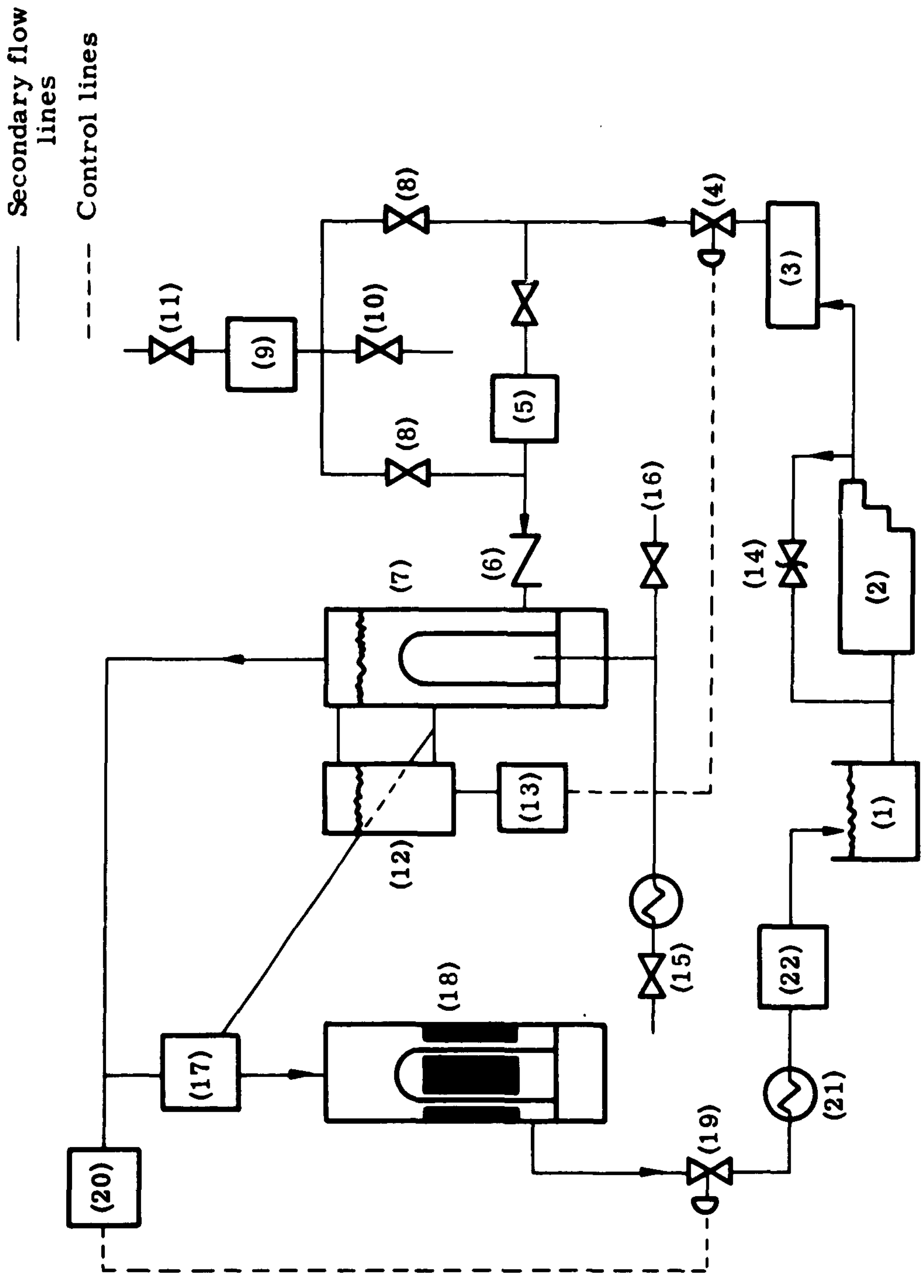


Fig. 7. Simplified Model Secondary Flow Schematic

around the sight gage and past a chemical feed tank (9). When chemicals are to be added, the bypass valves (8) are shut and the tank is drained (10), filled with chemicals (11) and topped with demineralized water to prevent an air pocket. The bypass valves (8) are then opened and water is fed through the bypass overnight.

The steam generator has a float chamber (12) attached to it so that the generator water level may be monitored by the level controller (13). The controller then adjusts the level control valve (4) so the water level is maintained above the hairpin tubes of the test vessel. Any excess pump discharge is bypassed around the pump through a relief valve (14). The steam generator has a blowdown port through the tube sheet through which deposits may be removed by passing the water through a cooling coil (15). Samples may be taken through the port (16) connected to the blowdown hole.

Steam produced by the generator leaves through the top of the vessel, goes through a steam separator (17) and into the superheater (18). Moisture and contaminants removed from the steam are returned to the generator. The steam passes along the superheater tubes and out of the superheater through the pressure control valve (19) which responds to the pressure controller (20). The steam is then condensed in a cooling coil (21) and the condensate goes through a flow meter (22) and back to the storage tank. The storage tank has an immersion heater in it to maintain the water in a deaerated condition.

C. MINIATURE SECONDARY SYSTEM

The four miniature heat exchangers are serviced by a single secondary system. The vessels are installed in a parallel flow arrangement between the feed and return manifolds. The system is constructed of 300 series stainless steel tubing connected by threaded fittings. The components are also stainless steel except for the line heater and the steam separator which are carbon steel.

A simplified flow schematic of the system is shown in Fig. 8. Water is drawn from the storage tank (1) by the constant volume circulating pump (2) and discharged through the circulating heater (3) where the water is preheated to the desired feed water temperature and into either the chemical feed manifold (4) or the normal feed manifold (5). Only one of the four vessels fed by these manifolds is shown in Fig. 8.

Water from the normal feed manifold goes through a shutoff valve, through the water level control solenoid valve (6), through a check valve (7) and into the miniature heat exchanger (8). A probe-type level controller (9) actuates the control valve to maintain the water

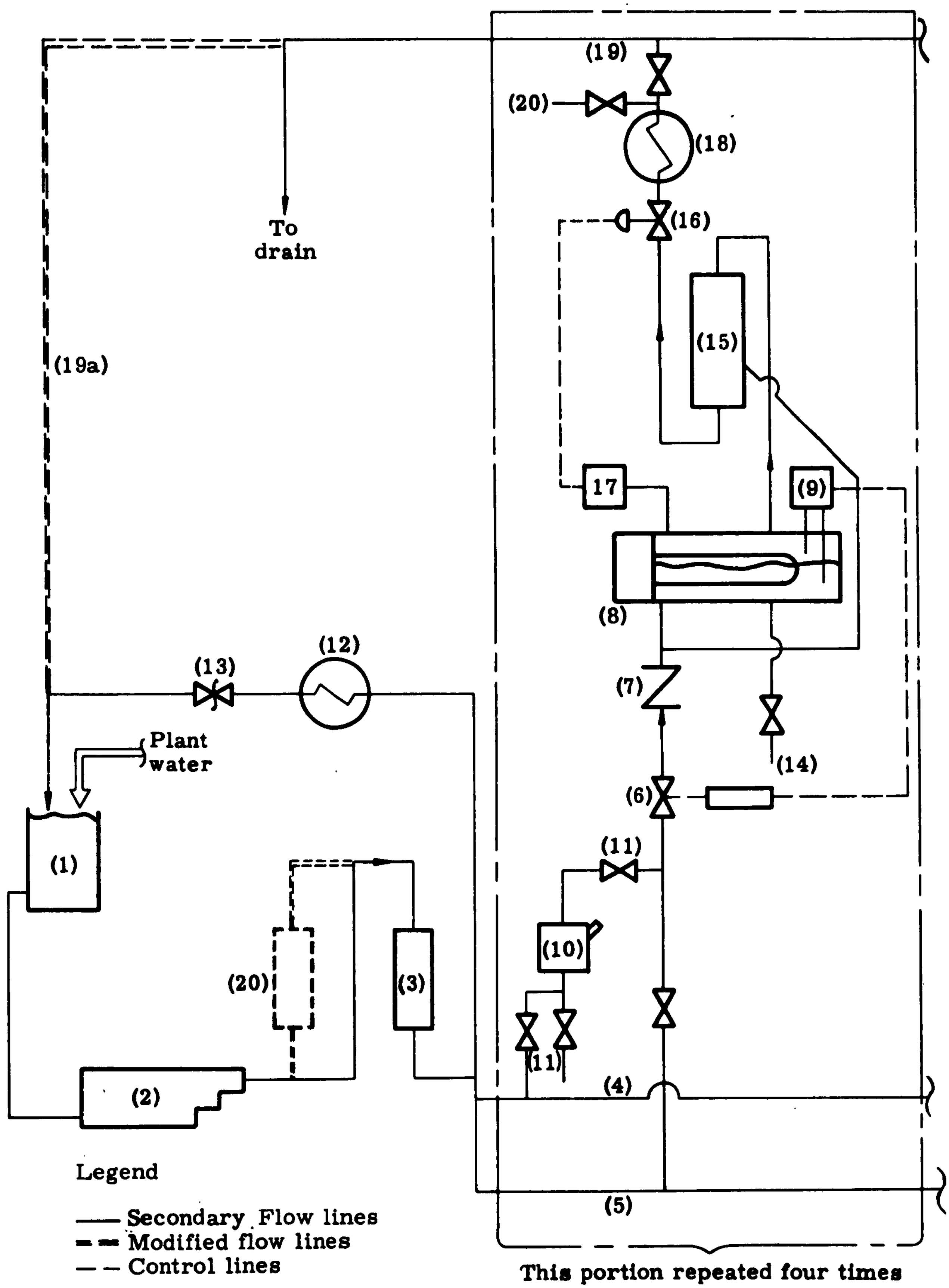


Fig. 8. Simplified Miniature Secondary Flow Schematic

level at the vessel centerline. If it is necessary to add chemicals to the feed water, the chemical feed tank (10) is filled with the chemicals and, by manipulating the shutoff valves (11), the feed water passes through the chemical feed tank. When none of the vessels are being filled, the pump discharge goes through a cooling coil (12), a relief valve (13) and back to the storage tank. The water is cooled only sufficiently to keep the storage tank water warm enough to remain deaerated.

Each miniature test vessel has a sample port (14) on the bottom of the secondary shell. Generated steam leaves the top of the vessel and passes through a steam separator (15) where moisture and entrained chemicals are removed and returned to the vessel. From the separator the steam goes through a pressure control valve (16), which responds through a controller (17) to the vessel pressure and into a cooling coil (18) where it is condensed. This condensate goes into the return manifold (19) and then to a drain. A port (20) is provided for sampling the condensate.

The system described was used to test MIN 10, 11, 15 and 16. However, as noted in Chapter IV, this arrangement was modified for the tests of MIN 13, 14, 18 and 19. Water discharged from the pump was sent through a demineralizer resin bed (20) before going into the circulating heater. The return manifold (19) was run to the storage tank (19a) instead of to a drain, and plant water additions to the storage tank were discontinued.

IV. TEST OPERATIONS

A. PREPARATION FOR TESTS

1. Cleaning of the Systems

After installing the test vessels, it was necessary to perform certain tasks prior to actually starting the tests. The facility had been modified in the period preceding this series of tests and it was necessary to ensure the integrity of the modifications. The primary and secondary systems were hydrostatically tested. This included the vessels since these are integral parts of the systems. The systems were then run at operating conditions for a short while to check the electrical control system and the adequacy of the power equipment.

After the hydrostatic, electrical and equipment tests, the systems were cleaned to remove accumulated dirt, grease, etc., which were present in some of the new system components and fabricated piping and tubing. The systems were cleaned with a solution of Oakite 90 (4 to 6 oz/gal), heated to $\sim$ 180° F and circulated for one hour. The model vessel hairpin tubes were examined through the vessel inspection ports; large amounts of surface dirt still remained. A second cleaning with the Oakite 90 solution failed to remove enough of the material to make the corrosion tests meaningful using the prescribed water conditions.

The systems were then cleaned with a 5 wt % solution of sulfamic acid. This was circulated for one hour at $\sim$ 180° F and then flushed three times with water containing some neutralizer (Na_3PO_4). The system was flushed with demineralized water until the effluent pH was neutral. After each system was cleaned, the entire system was flooded with demineralized water and left static until testing was started following the cleaning of the other systems. (This procedure was repeated on the miniature secondary system when the second series of test vessels were installed.)

2. Achieving Test Conditions

After the system was filled, the procedure to achieve test conditions consisted of pressurizing the primary loop, circulating the primary water through the test vessels and raising the primary water temperature to that required for the tests. As the primary temperature increased beyond the secondary saturation temperature, water was boiled out of the superheaters and then the steam generators. The secondary water level control devices were then automatically activated to maintain the proper secondary water levels. The same

process applied to the miniature vessels except for the absence of the superheaters.

When the desired primary water temperature was reached, the secondary steaming rates were adjusted, as required, until the proper rates were achieved. Chemicals were then added to the secondary water in the vessels. The addition of the chemicals was regarded as the start of test time.

B. TEST CONDITIONS

1. Measuring Conditions

The loop facility is fully instrumented so that all operating conditions may be monitored to determine satisfactory operation and to protect all loop components. However, only certain of these measurements are of interest for the corrosion tests. Each morning the following values were recorded in the data log book. Those followed by (CR) were continuously recorded on control panel instruments to provide a record of the operating conditions throughout each 24-hour period.

Primary system pressure, psig (CR)
Vessel secondary pressure, psig (CR)
Model vessel primary flow rates, gpm (CR)
Model vessel steaming rate (condensate), gpm (CR)
Model superheater primary flow inlet temperature, °F (CR)
Model steam generator primary flow inlet temperature, °F (CR)
Model steam generator primary flow outlet temperature, °F (CR)
Model steam generator secondary water inlet temperature, °F (CR)
Model superheater secondary steam outlet temperature, °F (CR)
Storage tank water temperature, °F

Test time was measured from the vessel pressure records. All the time that test pressure was maintained was considered as test time.

2. Maintaining Test Conditions

The prescribed test conditions are listed in Table 3 with some of the actual test conditions. The conditions best held were the system pressures. This is because they are independent of other conditions. The superheater inlet and miniature vessel inlet primary temperatures were slightly lower than specified--ranging from 446° to 452° F. This was principally because the control thermocouple is located somewhat upstream of the vessel inlets in the common flow

TABLE 3

Operating Conditions

System / Condition	Primary		Model Secondary		Miniature Secondary	
	Prescribed	Actual	Prescribed	Actual	Prescribed	Actual
Pressure (psia)	1200	1200	200	200	200	200
Steaming rate (lb/hr)	--	--	60	*	8	*
Primary flow rate (gpm)	--	*	--	--	--	--
Temperature (°F)						
Superheater primary inlet	450	~448	--	--	--	--
Miniature vessel primary inlet	450	~448	--	--	--	--
Secondary feed water	--	--	246	~280	246	~280
Steam generator secondary outlet	--	--	381	381	381	381
Superheated secondary steam	--	--	407	~395	--	--

*See text for range of values

stream (see Fig. 6) and the thermal losses varied slightly throughout the tests.

The secondary steaming rates were used as the determining factor for the primary flow rates. An attempt was made to keep the heat fluxes of the model vessels approximately constant; resulting steaming rates were between 57 and 63 lb/hr (or 60 lb/hr ± 5%). This was accomplished by taking weight-time samples twice a week and making an adjustment in the primary flow rate accordingly. As a result, the primary flow rate for these vessels varied from ~ 5.0 to ~ 4.2 gpm for the bimetal model vessels and ~ 4.4 to ~ 3.7 gpm for the Inconel model vessels.

The miniature vessel steaming rates were supposed to be maintained at 8 lb/hr which would have resulted in the same steaming rate per unit of heat transfer area as the model vessels. However, because of the physical arrangement of the system, the measured steaming rate of 8 lb/hr was a "net" rate. The measurements were made at the condensate sample port (see Fig. 8) which is downstream of the steam separator. The separator was uninsulated during the first series of tests and acted as a condenser as well as a steam separator. Hence, there was a greater steaming rate than was measured. This "gross" steaming rate is estimated to have been ~ 14 lb/hr. The separators were insulated for the second series of tests and a steaming rate of ~ 10 lb/hr was measured. The primary flow rates for these steaming rates are not known because of a malfunction in the flow instrument which occurred at an unknown time during the tests.

The desired superheat temperature was not achieved on the model vessels because of the facility limitations. The primary flow rate used in the tests provided the proper steaming rate. A greater quantity would have been required to raise the superheated steam temperature above the achieved range of 396° to 400° F (or 14° to 18° superheat). However, without a bypass around the steam generator this would have resulted in a greater steaming rate and it was decided to use the prescribed steaming rate as the governing criterion. (This problem is a result of the relative properties of the superheater and the steam generator. The opposite relationship in previous tests led to the addition of the superheater bypass shown in Fig. 6.)

The high secondary feed water temperature resulted from the heat conducted from the vessel along the heavy wall inlet feed pipe. The desired feed water temperature, 246° F, was achieved in the circulating heater and the additional heat was added just prior to injection into the vessel. The discrepancy was not noticed in the initial test period and it was decided not to make a change after the test was underway since it had little effect on the steam generator heat balance.

It should be noted that the specified operating conditions of Table 3 were set up prior to operation of the modified loop and were based on idealized conditions. They were specified for operational convenience. Hence, the corrosion data obtained are in no way prejudiced by the minor deviations from specified conditions.

C. WATER ENVIRONMENT CONTROL

Once each week a sample was taken from the primary system and the system makeup tank. Additions made to the tank were of demineralized plant water which had a resistivity of not less than 500,000 ohm-cm.

Three times each week the model secondary system was sampled at the steam generator blowdown connection and a port in the condensate return line. Chemical additions, when necessary, were made in the afternoon of the same day that the samples were taken.

Several occasions arose on which the chloride content of the model secondary environment exceeded the allowable limit. A few of these occasions were caused by inadequately demineralized makeup water. The storage tanks were sampled three times weekly and as soon as the condition was discovered the water was replaced with properly demineralized water. The other occasions of chloride contamination resulted from leaky condensate coils. Because of the very low pressure in the secondary side of the coil where the steam condenses, the pin hole leaks that developed there admitted plant water. This resulted in chloride in the storage tanks and subsequently in the model vessels.

In cases of minor chloride contamination, the condensate was dumped from the system and new water added to the storage tanks during an entire day. Purging of the system by this technique was possible because the steam separators were not entirely effective in removing carryover from the steam and some of it would pass through the superheater and back to the storage tank.

In cases of large chloride contamination, the primary flow was shut off and the steam generator drained through the blowdown port. The vessel was then filled and drained several times to flush it out. Upon resuming steam generation, the condensate was dumped for the rest of the day in the same manner as previously described.

The miniature system storage tank and vessels were sampled three times each week and the necessary chemical additions made the same afternoon. Because the steam separators did not prove sufficiently effective, the chemicals in the vessels were carried back to the common storage tank (see Fig. 8). This resulted in an undesirable

intercontamination of the environments. Therefore, shortly after the test began the steam condensate return lines were rerouted to the drain. Plant water was used for makeup.

Because the second series of miniature vessel tests, MIN 13, 14, 18 and 19, required secondary environments for two vessels with no chlorides, the described method using plant water (having about 14 ppm chloride) was not permissible. Therefore, smaller steam separators were installed in the system to reduce the carryover of contaminants and the steam condensate return lines were run back to the storage tank. Demineralized water was used for makeup; however, the reduction in intercontamination was still not sufficient and a demineralizer was added in the feed water line (see Fig. 8). This kept the intercontamination low but still evident. A blowdown and flush procedure similar to that used on the model vessels was employed when the contaminants became excessive. It was also necessary to make daily additions of the chemicals to replace those lost through the carryover.

D. ACCUMULATION OF TEST TIME

The period of facility operation required to perform the corrosion tests covered by this report extends from November 2, 1960, through July 31, 1961. A detailed calendar of the test time accumulated on each vessel during each day of this period is given in Appendix A. Inspection of the calendar will indicate that the test conditions were not maintained all of the time. Thus, the overall operating efficiency for the loop was about 73%. (The efficiency is the percentage of possible operating time during which test time was actually accumulated.) However, this figure is strongly influenced by time lost during the shakedown period following major loop modifications. During the latter portion of the program, after all major difficulties had been resolved, monthly efficiencies ranged between 88 and 97%.

Just after the corrosion tests were started, the primary system pressurizer heater failed. To get the program underway, argon was used to create a pressure head instead of steam as is the usual method. The combination of this and several minor malfunctions (which would be expected in the initial use of any facility) resulted in frequent loop shutdowns and short operating periods. Thus, a little more than 200 hours was accumulated during November 1960.

The test time accumulated during December was approximately 300 hours. However, once the loop was overhauled, a new pressurizer heater installed and many minor items repaired, the time accumulated was nearly continuous. This type of operation continued through January, February and March with the only major lost time being a six-day stretch in February for repair of a heater and the primary system circulating pump.

The remaining lost test time during this period as well as the majority of lost time during the succeeding months may be separated into the following three groups.

1. Primary System Shutdown

This may be caused by a plant water failure which would shut off the primary system circulating pump (loss of coolant) and this in turn would shut off the primary system line heaters. The loop would then cool down in a period of about eight hours. If excessive leakage did not occur as the flanges cooled, the water level and pressure were maintained. As a result the system could be started very quickly the next morning.

An electrical power failure had a similar effect on the loop. However, as the loop slowly cooled down, leakage would not be made up and pressure would be lost. The primary system generally required draining and refilling before resuming tests.

A third cause of this type of shutdown is the high temperature safety shutdown. This was initiated by a loss of the model steam generator water level, caused either by leakage or excess relief valve water passage. The resulting loss of a heat sink would cause the controlled line heater to shut off, but the other line heaters would remain on because they have on-off control. The primary temperature would rise to 512° F in about 18 hours when all of the heaters would be tripped off and the loop would cool to room temperature, as in the case of a plant water failure. The weekend of April 21 to 24 is an example of this type of failure where the No. 2 Model was steamed dry on the 21st and the tripoff occurred on the 22nd, some 21 hours later when the No. 1 Model was steamed dry. Testing was resumed again at 10 o'clock on the 24th.

2. Short Time Secondary Shutdown

This type of shutdown was of a few hours duration and affected only a specific vessel. The primary flow through the vessel was stopped and the vessel permitted to cool. The vessel might then be drained and flushed to remove water contaminants. The shutdown could also be performed so that the secondary system components could be repaired, i.e., the circulating pump relief valves may have needed reseating because of an excessive relief resulting in an insufficient feed rate. After the flushing or repair was completed, the vessel was filled to the proper water level and the primary flow reestablished. June 22 is an example of this type of shutdown of the Inconel model system.

3. Reduced Miniature Primary Flow Shutdown

This type of shutdown was caused by a reduction in the miniature vessel primary flow rate. The throttle valve controlling this flow was sometimes so near to being closed that it would "walk" closed because of vibration. Thus, the miniature vessels would shut down at random times during the night. This was a much more frequent occurrence with the second series of miniature vessels because of the lower gross steaming rate and consequent lower initial primary rate before the closing down of the valve. June 20th is an example of this type of shutdown. The vessels cool only partially since the primary system was not entirely shut off. However, insufficient heat was available to maintain the proper steam pressure. This type of shutdown had no effect on the model vessels and testing was resumed merely by opening the throttle valves.

These three types of shutdowns resulted in different treatment of the vessels. The vessels could experience a slow cooling to room temperature over six to eight hours with the re-establishment of operating temperature accomplished in less than one-half hour. The shutdown was in some cases preceded by a temperature rise of almost 70° F above the operating temperature with the accompanying steaming dry of the vessels. During a short time shutdown the vessel normally cooled to only 325° F (a saturation pressure of ~ 100 psia) before the primary flow was resumed. The vessel then reached operating temperature in less than 15 minutes. There was no readily evident effect on the corrosion test parameters because of tnese conditions (see Chapter VI).

The water used to refill the primary system when dumping was necessary was almost always deaerated first since this was necessary to protect the circulating pump. The water used to refill the secondary systems was rarely deaerated. Because of the small secondary storage tank heaters, it was not possible to deaerate the water when continuous dumping to eliminate the contaminants necessitated continuous additions to the storage tank.

V. ENVIRONMENTAL CHEMISTRY

The heat exchangers were tested under greatly varied environmental conditions ranging from high quality water normally specified for secondary conditions in reactor plants to very impure water which provides a severe test for the material being evaluated. The two sets of model vessels and two miniature vessels were tested with reactor quality secondary environments. The remaining six miniature vessels were tested with high chloride in the secondary water.

Some difficulty was encountered in maintaining the specified water conditions. In one or two instances it seemed that chloride appeared spontaneously; however, after a thorough examination the explanation was always found.

The makeup water for all of the test heat exchangers was maintained in excess of 180° F to expel dissolved oxygen. Thus, about 0.1 to 0.3 ppm oxygen remained dissolved in the feed water. In some instances there was no further treatment for the removal of oxygen, while in other tests sodium sulfite was added to remove the small amount of dissolved oxygen that did enter in the feed water.

MIN 10, 11, 15 and 16 were tested simultaneously. Since highly impure conditions were specified for the test environments, tap water was used for makeup. MIN 13, 14, 18 and 19 were also tested simultaneously. Two of these, MIN 14 and 19, had high purity test environments so all of the makeup water passed through a demineralizer immediately before entering the test vessels (see Fig. 8).

The chloride concentration in MIN 11, 13, 15 and 18 averaged somewhat lower than the specified values. In MIN 16 and MIN 19 the chloride concentrations were about right while those of MIN 10 and MIN 14 were somewhat high. The control of the pH presented no particular problem in any of the vessels. The chloride fluctuation for MIN 10, 11, 15 and 16 was primarily caused by the steam separators not effectively removing entrained moisture from the steam and this resulted in a carryover of chemicals from the vessels to the common storage tank. Since all of the heat exchangers did not have exactly the same steaming rate, there was some interchange of environmental constituents.

Operation was improved by diverting the condensate return line to the drain rather than to the makeup tank. This prevented interchange of chemicals from one vessel to another. However, environmental chemicals were lost more rapidly and, therefore, additions of makeup chemicals were made more frequently.

The variations of environmental constituents in MIN 13, 14, 18 and 19 were partially solved by installation of new separators and the previously mentioned makeup pump effluent demineralizer. The demineralizer was reasonably effective in removing contaminants carried from the storage tank into the feed water. However, occasionally the chloride concentration in MIN 14 and 19 did exceed the 0.5 ppm specified. When this occurred, the vessels were flushed until the specified conditions were established.

A. MIN 10 AND MIN 11

The secondary environments of the miniature Inconel vessels, MIN 10 and MIN 11, contained 1000-ppm chloride in each vessel. The pH was maintained at 10 with sodium hydroxide in MIN 10 and with a mixture of 33% Na_3PO_4 and 67% Na_2HPO_4 in MIN 11. Nineteen sodium chloride additions, averaging 1.6 grams each, were added to MIN 10 during the course of the test and 35 sodium chloride additions, averaging 1.6 grams each, were added to MIN 11. The difference in the number of chloride additions between MIN 10 and MIN 11 is a rough measure of the efficiency of their respective steam separators.

As previously stated, the environments in these two vessels were very severe. Earlier static secondary tests (Ref. 7) had indicated that high chloride combined with pH adjustment with sodium hydroxide produced a pale yellow-green film over all of the Inconel surfaces exposed to the water phase, whereas, a similar environment where pH was adjusted with trisodium phosphate did not. These most recent tests were intended to further investigate the effect of pH adjustment in a dynamic system.

MIN 10 was tested 3045 hours without failure and MIN 11 was tested 3024 hours without failure.

B. MIN 13 AND MIN 14

The secondary environment in one of the two Monel heat exchangers, MIN 13, contained 1000-ppm chloride and pH was adjusted to 10 with a 67% disodium, 33% trisodium phosphate mixture. The other vessel, MIN 14, contained secondary water of reactor quality--0.5-ppm chloride maximum, pH 10 with a trisodium phosphate solution free of "excess hydroxide" according to the Whirl-Purcell curve (Ref. 9), 10-ppm SO_3 and 200-ppm maximum total solids.

Thirty-five sodium chloride additions, averaging 3.5 grams each, were required to maintain the desired chloride concentration in MIN 13. On occasion there was some minor carry over of chloride into MIN 14 which necessitated flushing with demineralized water until the chloride concentration was within specification.

MIN 13 was tested for 1393 hours with no failure; MIN 14 was tested for 1418 hours with no failure.

C. MIN 15 AND MIN 16

The water conditions for the miniature bimetal vessels, MIN 15 and MIN 16, were 800 ppm chloride, and the pH adjusted to 10 with a mixture of 33% Na_3PO_4 and 67% Na_2HPO_4. Thirty-eight sodium chloride additions, averaging 1.7 grams each, were added to MIN 15 during the course of the test and 34 sodium chloride additions, averaging 1.3 grams each, were added to MIN 16.

The tests with MIN 15 and MIN 16 were intended to define the extent of galvanic protection in the bimetal system. MIN 16 was intentionally defected by filing away the low carbon steel facing the secondary environment to expose the stainless steel. Defects of two sizes, 1/8 inch by 1/8 inch and 1/8 inch by 3/4 inch, were machined on the tubing exposed to the vapor phase, the liquid phase and at the vapor-liquid interface (see Fig. 3). No leaks were found in either vessel over their test life of 3019 and 3035 hours for MIN 15 and MIN 16, respectively.

D. MIN 18 AND MIN 19

The secondary environment in one of the two nickel heat exchangers, MIN 18, contained 1000 ppm chloride, and the pH was adjusted to 10 with a mixture of 67% disodium phosphate and 33% trisodium phosphate. The environment of the other nickel heat exchanger, MIN 19, contained 0.5 ppm chloride maximum, 10 ppm SO_3, 200 ppm maximum total solids, and the pH was adjusted to 10 with a trisodium phosphate solution, the same as used in MIN 14.

Thirty-five sodium chloride additions, averaging 3.5 grams each, were required to maintain the specified chloride environment in MIN 18. Again, it was necessary, on occasion, to flush the secondary system of MIN 19 to reduce the slight excess of chloride which accumulated.

MIN 18 was tested for 1385 hours without failure; MIN 19 was tested for 1350 hours without failure.

E. MOD SG-4 AND MOD SH-4--BIMETAL

Considerable difficulty was encountered in trying to maintain the specified secondary water conditions of the SM-1 plant, in MOD SG-4. The desired environmental conditions were $<$ 0.5 ppm chloride, $<$ 0.5 ppm oxygen, controlled by maintaining 10 ppm sodium sulfite, 200 ppm total solids and pH adjusted to 8.5 with trisodium phosphate. During the entire testing period, the secondary makeup tank was maintained above 180° F to expel most of the oxygen. The difficulty centered around chloride contamination. The source of the chloride contamination was ultimately traced to a thin film of corrosion products with occluded chloride in the blowdown coils. The chloride was leached slowly from the corrosion film into the secondary solution. The blowdown coils had been cleaned after previous use but, apparently, a minute amount of corrosion product remained. After recleaning the coils and extended flushing of the secondary system with demineralized water, the chloride concentration remained within the specification.

The bimetal model steam generator and superheater were service tested for 4890 hours.

F. MOD SG-7 AND MOD SH-7--INCONEL

The difficulties encountered in operating this set of heat exchangers were much the same as those encountered in operating the bimetal vessels. The desired environmental controls were $<$ 0.5 ppm chloride, 10-ppm sodium sulfite to remove dissolved oxygen, 150 ppm PO_4 added as trisodium phosphate and a pH of 10 to 10.5. Again, chloride contamination was a problem. The source of the chloride in the steam generator was eventually traced to a small leak in the condensate cooling coils. The leak permitted tap water to enter the condensate return line and thence into the secondary water makeup tank. Replacement of the coil and extended flushing of the secondary system with demineralized water reduced the chloride concentration to within specification.

The Inconel steam generator and superheater were service tested for 4747 hours.

VI. HEAT TRANSFER INDEX

The heat transfer index was derived to give an indication of any changes occurring in the vessel heat transfer properties. Because scale or corrosion products affect the quantity of heat transferred, the index should give an indication of scale buildup. The index is essentially a measure of the relative efficiency of the vessel using an "ideal" case as a basis and is derived for the steam generator as follows:

$$\text{Heat transfer index} = \frac{\text{Heat transferred to secondary fluid}}{\text{Primary fluid heat available for transfer}}$$

$$\text{Heat transfer index} = \frac{w_s \, (H_{so} - H_{si}) + Q_L}{w_p \, (H_{pi} - H'_{po})} \qquad (1)$$

where:

w_s = secondary steaming rate, lb/hr

w_p = primary flow rate, lb/hr

H_{si} = enthalpy of secondary water in, Btu/lb

H_{so} = enthalpy of secondary steam out, Btu/lb

H_{pi} = enthalpy of primary water in, Btu/lb

H'_{po} = enthalpy of primary water out, if at the secondary steam saturation temperature, Btu/lb

Q_L = thermal losses from the vessel, Btu/hr

After the data were carefully examined, it was determined that a more accurate index could be determined by using the primary fluid measurements because those data were taken more often during the test. The heat balance for the steam generator may be written:

$$w_s \, (H_{so} - H_{si}) + Q_L = w_p \, (H_{pi} - H_{po}) \qquad (2)$$

where:

H_{po} = enthalpy of primary water out, Btu/lb

Substituting in Eq (1):

$$\text{Heat transfer index} = \frac{w_p\,(H_{pi} - H_{po})}{w_p\,(H_{pi} - H'_{po})} = \frac{H_{pi} - H_{po}}{H_{pi} - H'_{po}} \qquad (3)$$

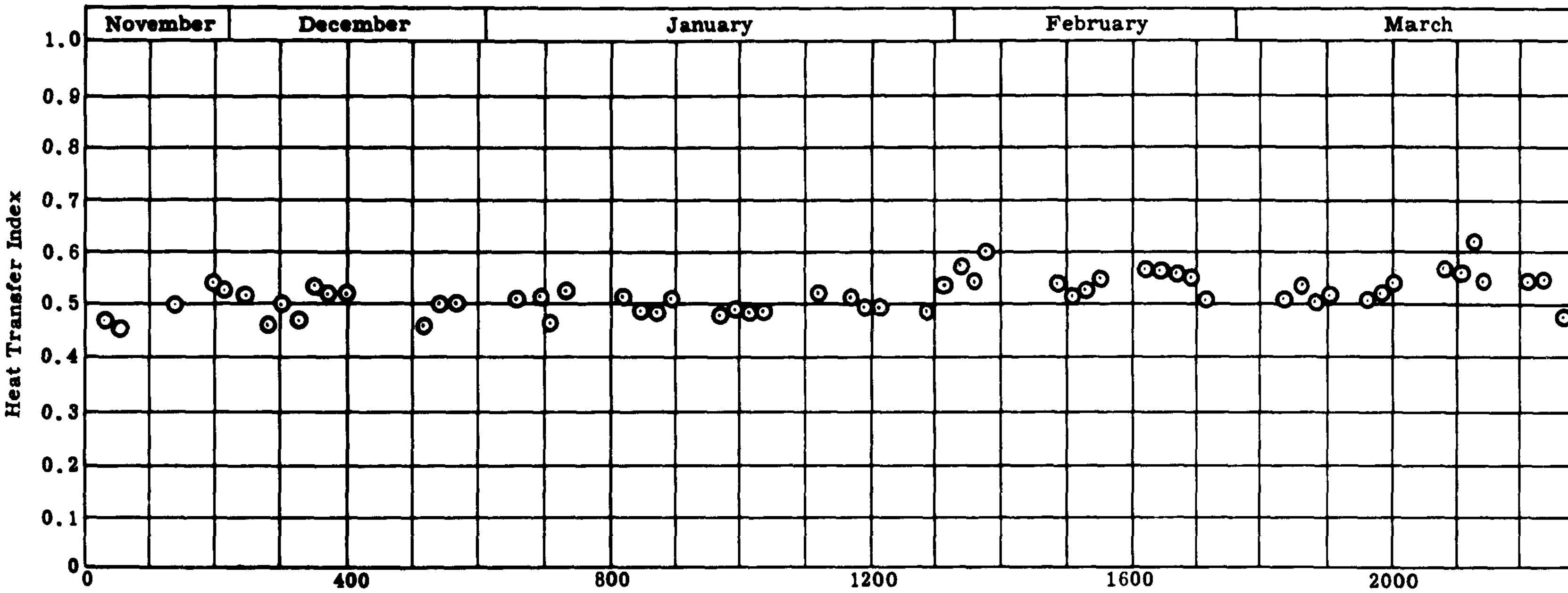
The values of the index are shown in Figs. 9 and 10. Each has an approximately equal distribution of the 130 values with respect to test time. The calendar time span is also noted for comparison.

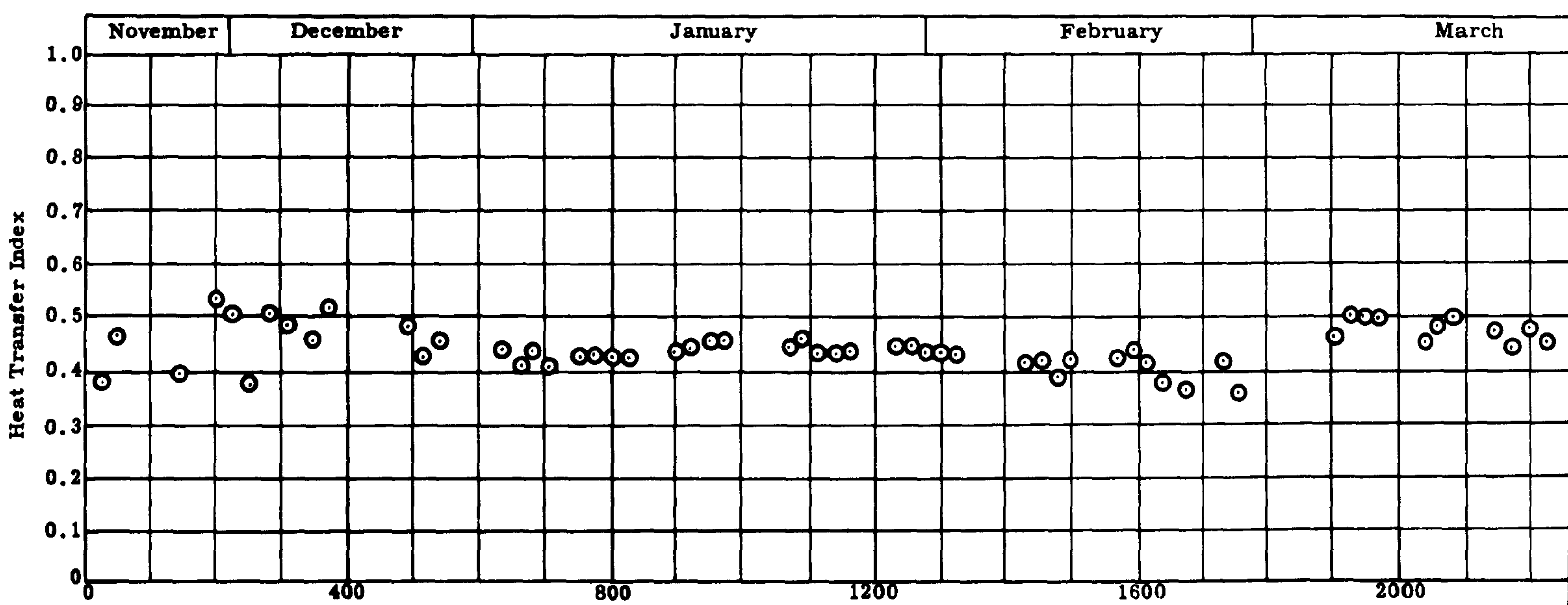
Numerous cross plots of each index were made including the parameters of primary flow rate, w_p, primary inlet enthalpy, H_{pi}, heat flux, $w_p\,(H_{pi} - H_{po})$, and primary outlet enthalpy, H_{po}, as well as the index denominator $(H_{pi} - H'_{po})$ and the numerator $(H_{pi} - H_{po})$. The index appeared independent of all of these except, rightly, the outlet enthalpy and the numerator.

The index for the Inconel vessel, Fig. 9, is nearly constant with the exception of two periods of an ~10% increase, 1250 to 2250 hours and 3100 to 3450 hours. However, this is not much more than some of the data scatter, and an external influence may have caused it and still gone undetected in the cross plots.

No relationship was found between testing events such as flushing or high temperature and the variations in the index. The values for the initial test hours in December show no more scatter than the later values. It would seem that the film that was found either formed very quickly or developed during the first contact with water and was not removed by the Oakite 90 or sulfamic acid cleanings. If the film formed quickly, it could have been during shakedown, startup, the first few hours of operation or during the frequent shutdowns which occurred in December. The index for the Inconel vessel should therefore be regarded as unchanged during the nearly 5000 hours of service.

The index for the bimetal steam generator, Fig. 10, was also found to be properly independent using the cross plots. The index, however, does appear to have changed with test time with three distinct regions--a gradual slight reduction approaching 1800 hours, an increase of ~8% above the original value at 1900 hours and a gradual reduction to the original value at 4000 hours. This was followed by a steep increase to 20% over the original value at 4400 hours. The first of these steps was not accompanied by any particular change in the test conditions. However, the vessel was steamed dry and subjected to high temperature operation just before the first of the higher values was recorded (at 1900 hours).


November
December
January
February
March
Heat Transfer Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
800
1200
1600
2000


November
December
January
February
March
Heat Transfer Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
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0.1
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400
800
1200
1600
2000

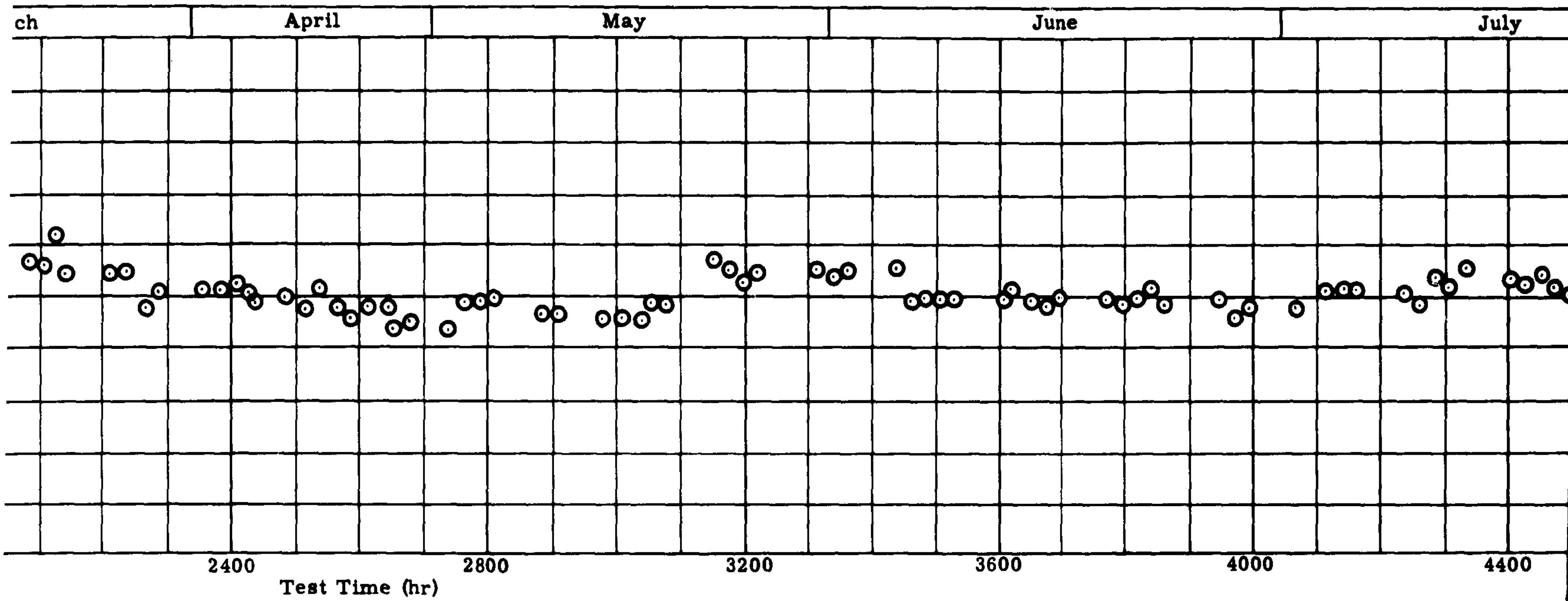


Fig. 9. Variation of Heat Transfer with Time--Inco

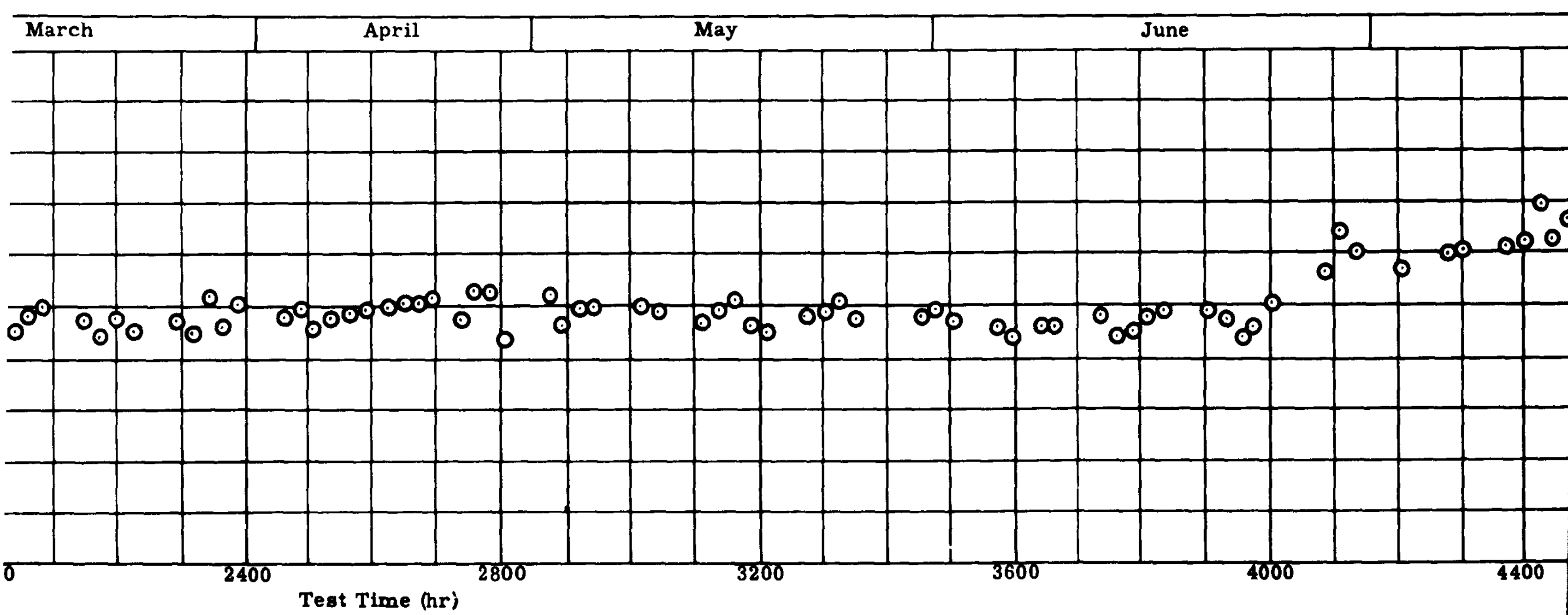


Fig. 10. Variation of Heat Transfe
Generator (Mod SG-4)

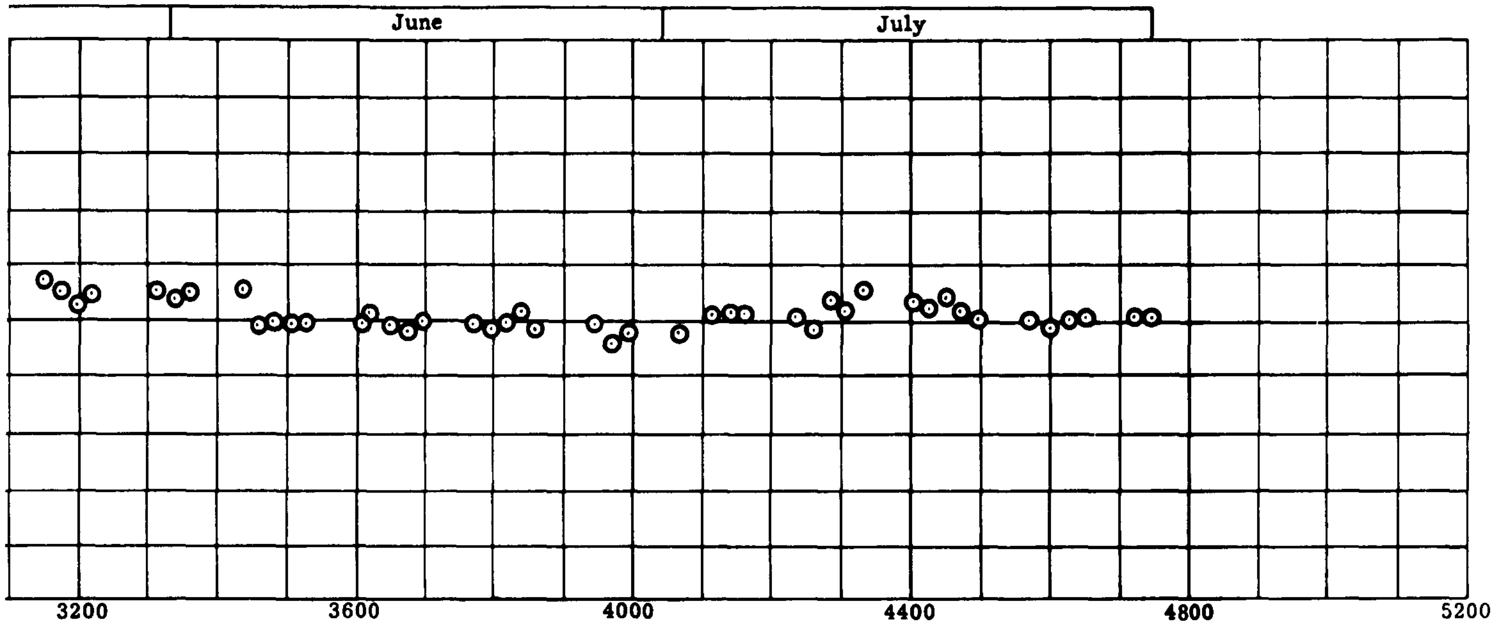


Fig. 9. Variation of Heat Transfer with Time--Inconel Steam Generator (MOD SG-7)

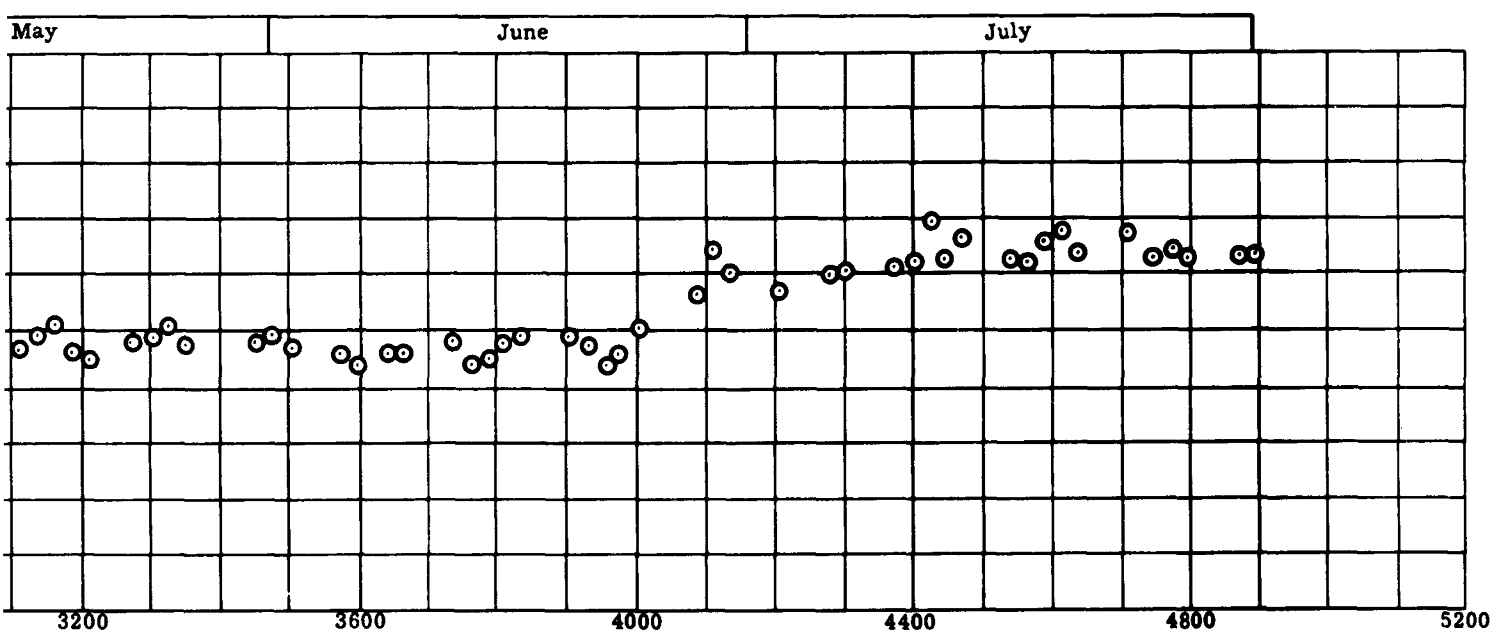


Fig. 10. Variation of Heat Transfer Index with Time--Bimetal Steam Generator (Mod SG-4)

3

The 20% increase after 4000 hours was accompanied by noticeable changes of the test parameters. The steaming rate increased noticeably and a reduction in primary flow was necessary from ~4.6 to ~3.1 gpm (mean values) over the period from 4080 to 4400 hours. There was a sharp decrease in primary outlet temperature of ~7° F at 4080 hours. The measurements were independently checked to verify these changes and withstood the examination. The only transient event to occur between the first and second points after 4000 hours was a gradual reduction of the primary flow because of a faulty control valve. This occurred 20 test hours before the second index point and the vessel sat cold for nine hours before being started again. The startup was normal, and operating temperature was achieved in a little less than one hour. The Inconel vessel was subjected to identical treatment.

It is difficult to do more than speculate about what occurred in the steam generator. The 25-day period just before 4080 hours, Fig. 10, was the longest continuous test run and the period before 1900 hours was one of the longer periods. It is conceivable that there was a crud buildup until the shock of the rapid startup broke it off as a result of differential thermal expansion between the tube and the crud. However, the vessel was steamed dry six or seven other times and there is no corresponding step in the index for the resulting startups or any other startups. There is no record of any event which occurred only once to provide a satisfactory explanation of the 20% increase. The index values for December show so much scatter that the index at the start of the test could have been higher than the final index and decreased in the time from a few to 200 hours. The cleaning of the tubes with Oakite 90 and sulfamic acid may also have been incomplete; the view through the inspection ports is limited. The only conclusion which can be reached is that the steep increase existed but is unexplainable from our data.

VII. TEST RESULTS

A. MIN 10--INCONEL

MIN 10 was tested for 3045 hours in a secondary environment containing 1000-ppm chloride; pH was adjusted to 10 with sodium hydroxide. Figure 11 is a close up of the appearance of the tubes after testing and before they were cleaned. The tubes were covered with a rather loosely adherent boiler scale. Samples of the deposit were removed from portions of the tubes exposed to both the water and vapor phases. X-ray diffraction analysis indicated that $CaSO_4$ was the major constituent and $CaCO_3$ was the minor constituent in the deposit from both the vapor and liquid phases. Emission spectroscopy indicated that the major constituents of the deposit were Ca, Si, Fe and Mg. Baltimore City tap water was used for makeup throughout the tests of MIN 10, 11, 15 and 16 since one objective of the tests was to further investigate the possibility of using untreated ground water in the secondary systems of military plants at remote sites. The use of tap water accounts for the heavy boiler scale. The pale yellow-green film which appeared on the submerged portion of the tubes in a previously tested Inconel vessel (Ref. 7), MIN 9, did not appear in MIN 10. However, the conditions were quite different in that the secondary system of MIN 9 was static while the secondary system in MIN 10 was dynamic, although both had the same chemical environment.

The tube that was expanded into the tube sheet (Nos. 2 and 3, Fig. 12) showed no penetration by the environmental chemicals in either phase while the unexpanded tube (Nos. 1 and 4) showed some penetration particularly in the vapor phase. The deposits evident on the tube and tube sheet in Fig. 12 resulted from a concentration of salt dissolved in the secondary environment. However, metallographic sections of both the tubes and the tube sheet adjacent to the areas of penetration showed no detrimental effects (Fig. 13).

Examination of the tubing after cleaning revealed some attack on the secondary surface. Some incipient attack and a few shallow isolated pits--the deepest was three mils--were found. The attack was slightly more prevalent on the surface that was exposed to vapor than on the surface exposed to liquid. The extent of pitting suggested possible ferrite contamination of the surface.

The exceptional resistance of Inconel to corrosive attack under severe environmental exposure is obvious. The Inconel tubing in this test vessel suffered only minor attack after more than 3000 hours in a hot solution containing high chloride, some oxygen and numerous other dissolved materials. The tubing suffered very little general

Fig. 11. MIN 10--Appearance After Test

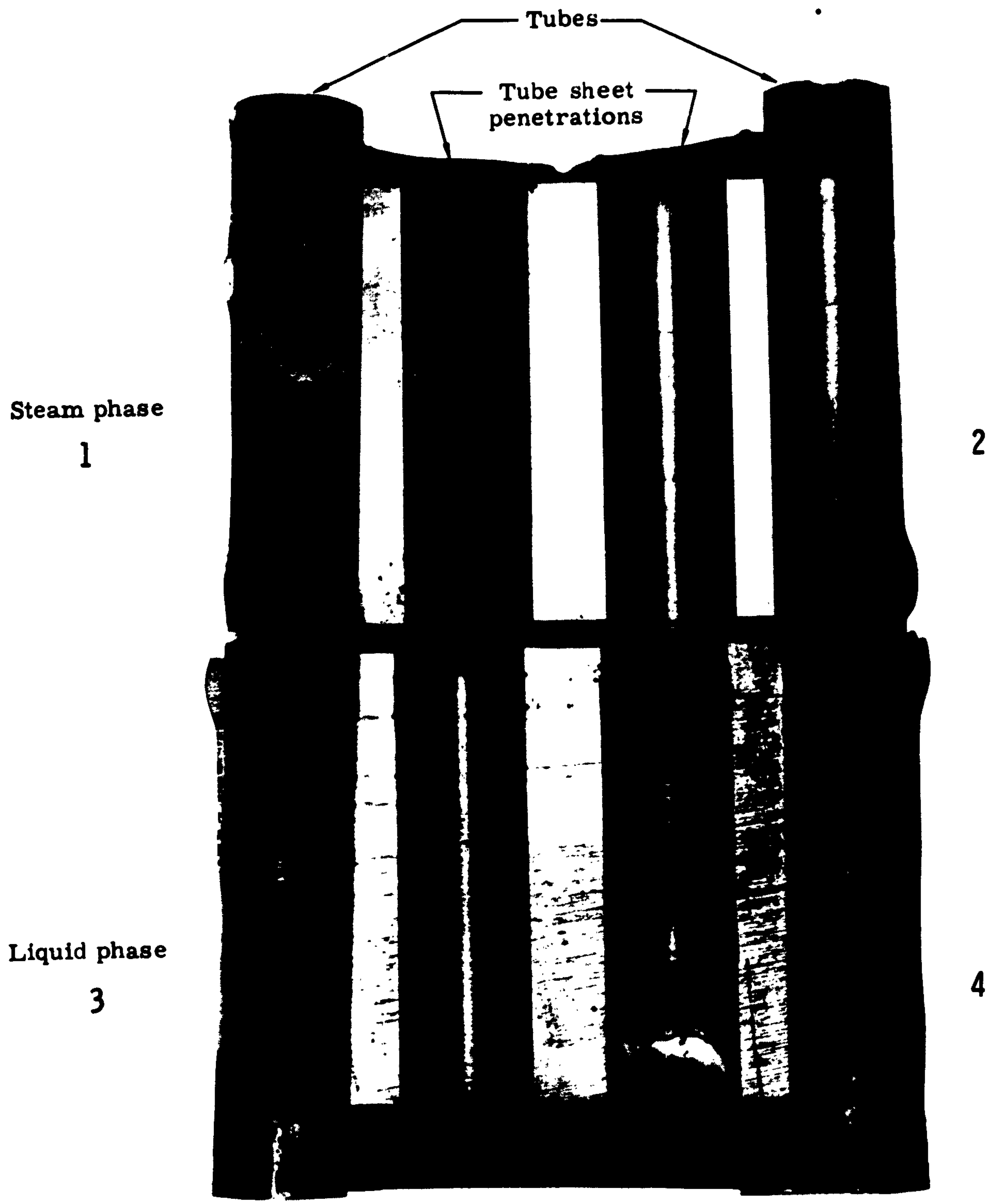


Fig. 12. MIN 10--Longitudinal Cut Through Tubes in the Tube Sheet Showing the Effect of Rolling

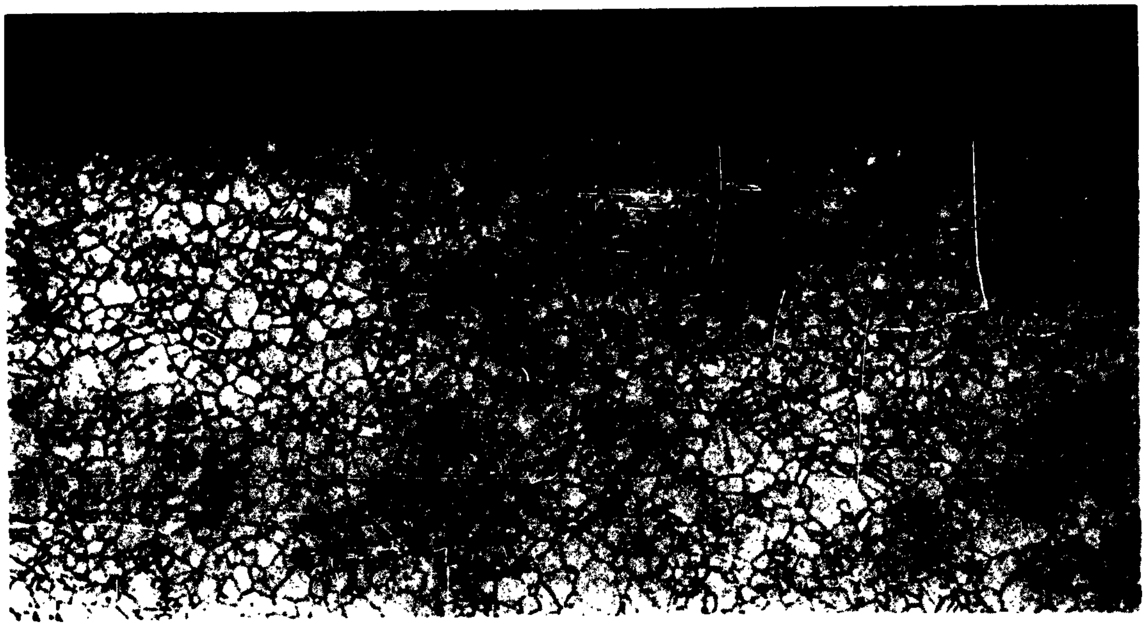


Fig. 13. Metallographic Section of Inconel Tubing from Crevice Penetrated by Environment--No Corrosive Attack Occurred

corrosion as the scores and scratches from fabricating were still clearly apparent after cleaning the tubes. Figure 14 shows a portion of the tubing after cleaning.

B. MIN 11--INCONEL

MIN 11 was tested for 3024 hours in a secondary environment containing 1000-ppm chloride; pH was adjusted to 10 using 33% Na_3PO_4 and 67% Na_2HPO_4. Figure 15 shows the appearance of the tubes after test. X-ray diffraction analysis indicated that $CaSO_4$ was the major constituent and $CaCO_3$ was the minor constituent of the scale that formed on the tubes in both the vapor and the liquid phases. Emission spectroscopy showed that the deposits in both vapor and liquid phases were about the same as those found in MIN 10. Although the tubes exposed to vapor were covered with boiler scale, there were some isolated areas where bright metal was evident. The tube surfaces were bright and lustrous after cleaning and similar in appearance to that shown in Fig. 14.

The tube with the expanded joints suffered no environmental penetration in either phase, as shown in Fig. 16. The unexpanded tube joints, Nos. 1 and 4, showed penetration, particularly in the vapor phase. There was no distinguishable difference in the test results with MIN 10 and MIN 11 with respect to the environmental difference of the pH adjustment. The results of MIN 11 with respect to pitting duplicated the results with MIN 10. There was isolated incipient attack with a few shallow pits--in this case the deepest pit found was five mils. For both MIN 10 and 11 detection of pits was not possible under direct visual examination. Inspection with a 30-power microscope was required.

C. MIN 13--MONEL

MIN 13 was tested for 1393 hours in a secondary environment containing 1000-ppm chloride; pH was adjusted to 10 with the 67% disodium, 33% trisodium phosphate mixture. The appearance of the tubes before cleaning is shown in Fig. 17. The secondary surfaces were free of any measurable quantities of foreign matter and showed only a very thin film of dark gray discoloration on both vapor and liquid surfaces. Demineralized water was used for makeup, accounting for the absence of the boiler scale which was observed on MIN 10 and 11 tube surfaces. X-ray diffraction analysis showed that Fe_3O_4 was the major constituent in the deposit found on the tubes in both the vapor and the liquid phases.

Fig. 14. Appearance of Inconel Tubing After Cleaning--MIN 10

Fig. 15. MIN 11--Appearance After Test

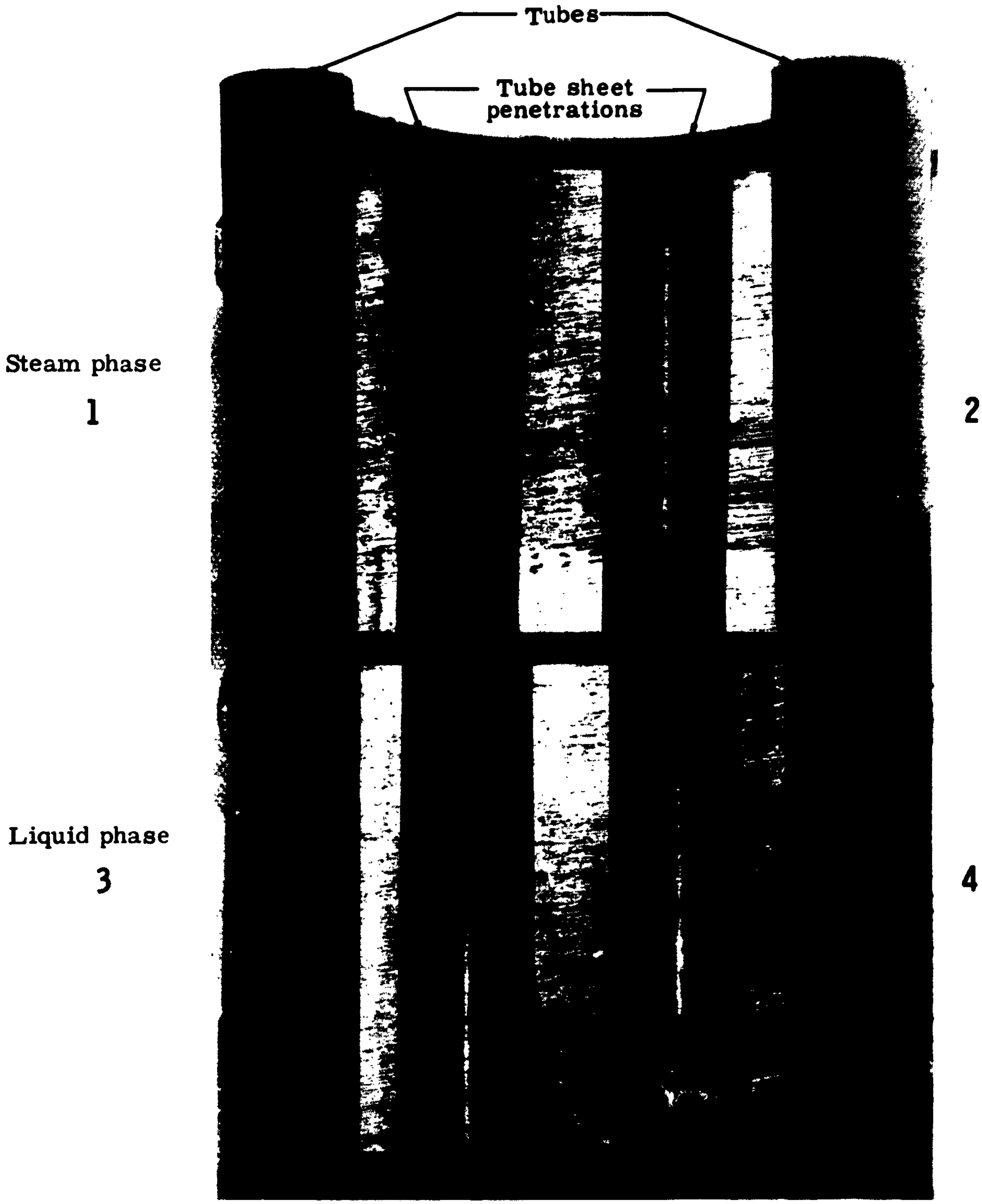


Fig. 16. MIN 11--Longitudinal Cut-Through Tubes in the Tube Sheet Showing the Effect of Rolling

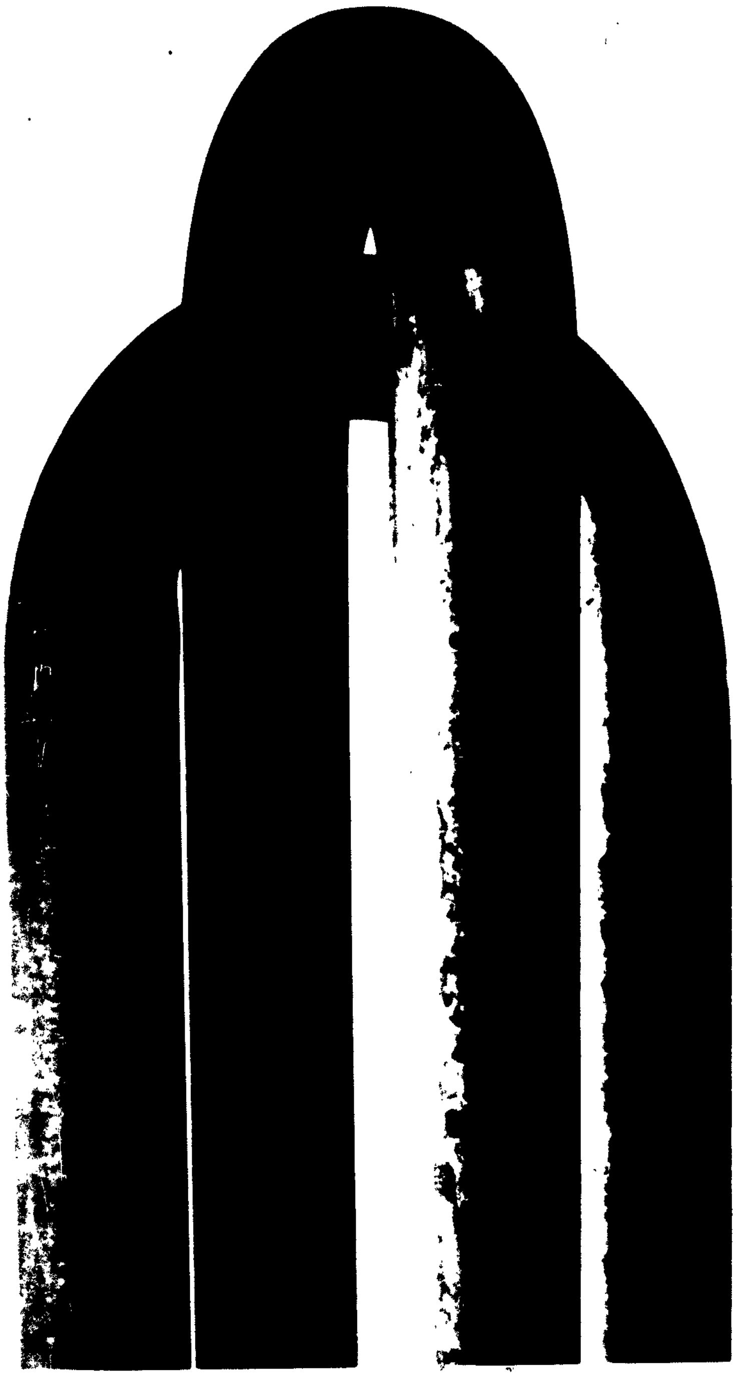


Fig. 17. MIN 13--Appearance After Test

The source of the Fe_3O_4 was the carbon steel tube sheet and shell. Emission spectroscopy showed that the composition of the corrosion product was quite complex, containing Ca, Mn, Si, Ni, Fe, Cu, Zn, Pb, Al and Mg. The film of corrosion products found on the tubes in the liquid phase was slightly darker than the film in the vapor phase. All of the tube-to-tube sheet joints were expanded in MIN 13, effectively excluding the environment.

Examination of the secondary surface of the tubing showed considerably more incipient attack and pits than were found on the Inconel tubes. The ratio of pits to areas of incipient attack was greater also than that found on the Inconel tubes. The depth of the pits ranged to a maximum of about three mils. Figure 18 shows typical areas of attack in both the vapor and liquid phases. The areas of attack are also typical of those which appear on all of the affected tubing whether Inconel, Monel or nickel. However the relative number of affected areas differs with the type of tubing.

D. MIN 14--MONEL

MIN 14 was tested for 1418 hours in a secondary environment containing 0.5-ppm maximum chloride, 10-ppm SO_3 and 200-ppm maximum total solids; pH was adjusted to 10 using trisodium phosphate. The submerged tubes were slightly darker than the tubes exposed to the vapor phase. Figure 19 shows the tubes after the secondary shell was removed. In MIN 14, all of the tube-to-tube sheet joints were expanded. There was no environmental penetration of any of these joints.

The results, so far as pitting was concerned, nearly duplicated the results of MIN 13, although the extent of pitting and incipient attack was somewhat less. However, the difference in the numbers of areas attacked did not reflect the difference in test environment, at least with respect to dissolved chloride. The secondary environment of MIN 13 contained 1000-ppm chloride while the environment of MIN 14 was virtually chloride free. The susceptibility of the Monel tubing to pitting is evidently not strongly dependent on the presence of chloride. Monel showed good resistance to general corrosion.

E. MIN 15--BIMETAL

MIN 15 was tested for 3019 hours in a secondary environment containing 800-ppm chloride; pH was adjusted to 10 with a mixture of 33% Na_3PO_4 and 67% Na_2HPO_4. The tubes were heavily coated with corrosion products as shown in Fig. 20. X-ray diffraction identified the

Vapor phase

Penetration = 1.5 mils

Water phase

Penetration = 1.1 mils

Fig. 18. MIN 13--Typical Pitted Areas (Magn 30x)

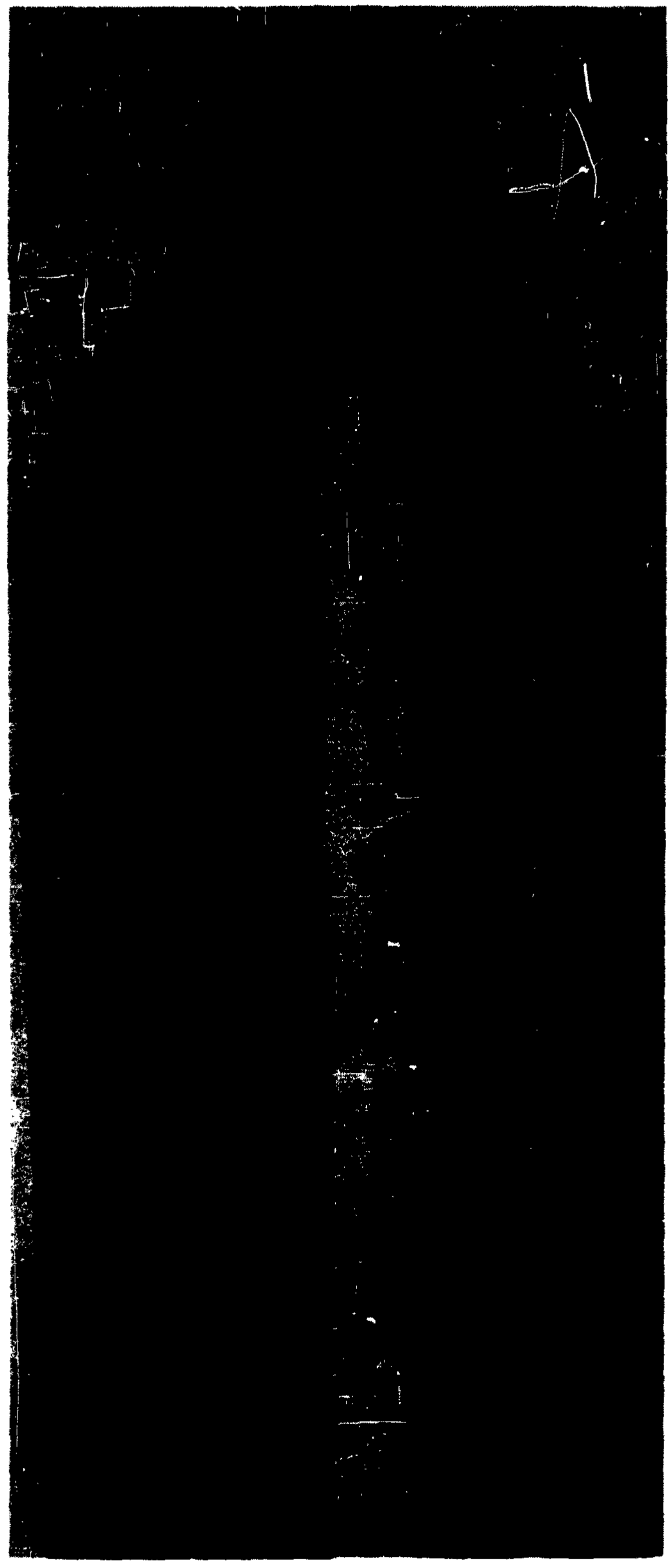


Fig. 19. MIN 14--Appearance After 1418 Hours of Testing

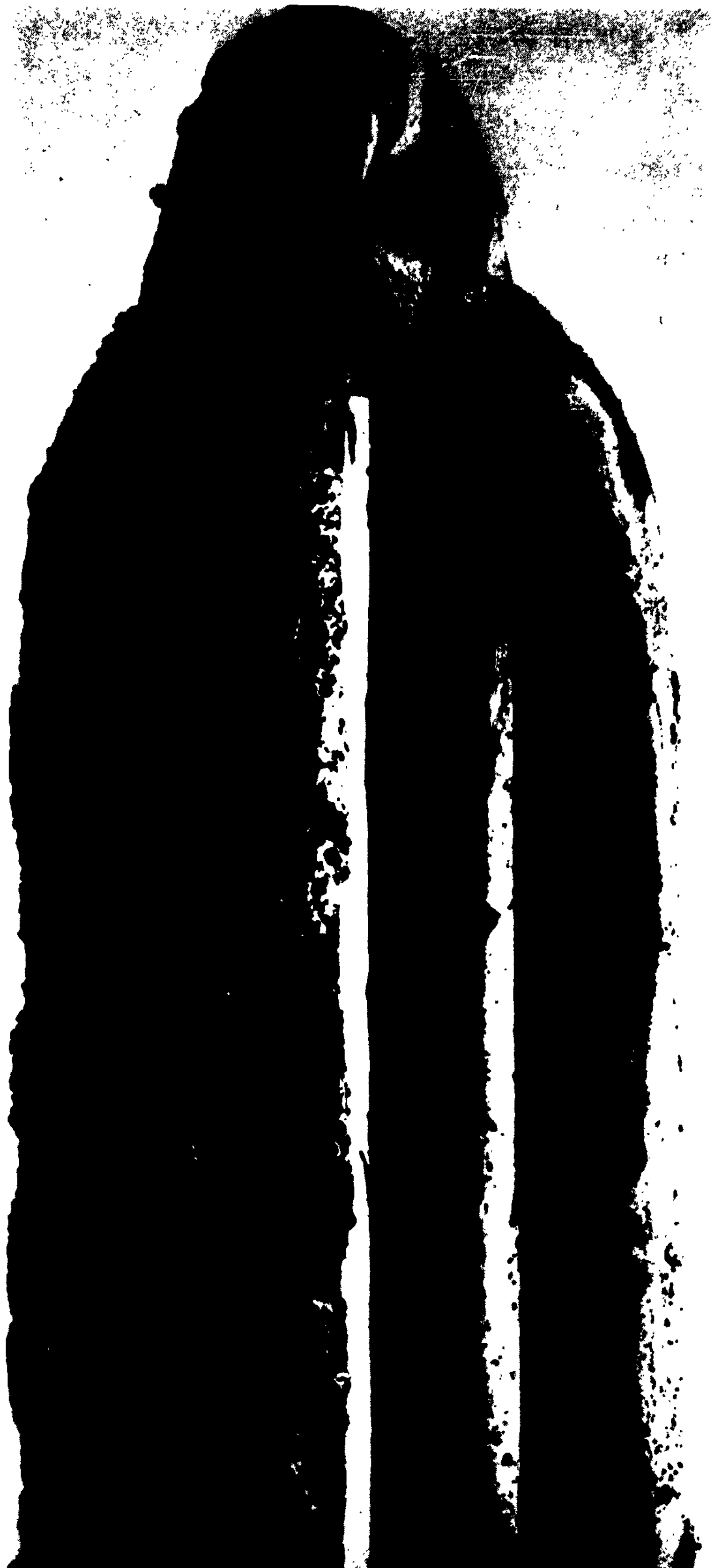


Fig. 20. MIN 15--Appearance After 3019 Hours of Testing

major constituent on the submerged tubes to be $CaCO_3$ and the minor constituent to be Fe_3O_4, with a trace of $CaSO_4$. The major constituent of the deposit in the vapor phase was found to be Fe_3O_4 with traces of $CaCO_3$ and $CaSO_4$. All of the tubes were expanded into the tube sheet. There was no penetration of any of these joints, as shown in Fig. 21.

The tubes were badly pitted, particularly in the vapor phase. This is clearly evident in Fig. 22 which shows the tubes after cleaning. There were a number of areas where the low carbon steel secondary clad had been penetrated completely, exposing small areas of stainless steel. The stainless steel suffered no detrimental effects from exposure to the severe environment, possibly because of cathodic protection by the surrounding sacrificial, low carbon steel anode.

F. MIN 16-BIMETAL

MIN 16 was tested for 3035 hours in an environment identical to that of MIN 15. The tubes were quite similar in appearance to those in MIN 15 after testing. Figure 23 shows the tubes heavily coated with corrosion products. X-ray diffraction and emission spectroscopy of the deposit from the tubes, both the vapor and liquid phases, showed that the composition was the same as that found in MIN 15. Likewise, the portions of the tubes that were exposed to the vapor phase had the same dark, almost black, corrosion products as found in MIN 15.

The tubing in MIN 16 was purposely defected by exposing the stainless steel sublayer as is illustrated in Fig. 24. Figure 25 shows one of the defected areas exposed to the liquid phase before cleaning. It was impossible to show a defected area in the vapor phase because of the very heavy layer of corrosion products. Figure 24 shows the tubing after cleaning. The defects and extent of corrosion are clearly visible. Gross amounts of the low carbon steel clad were corroded away. Metallographic sections from the areas of the defects revealed no detrimental effects, as far as the stainless steel was concerned. Typical photomicrographs are shown in Fig. 26. The most striking result of the tests with MIN 15 and 16 was the excellent resistance of the submerged low carbon steel tubing to the unusually severe conditions. This is illustrated in Fig. 24 and also in Fig. 26 which shows that in the liquid phase the tapered carbon steel portion of the defect is still present. In the vapor phase (Fig. 26-b) the portion has completely corroded away.

A rigid definition of the extent of cathodic protection would be very difficult. It could be argued that the chance exposure of a crack-susceptible area is remote; therefore, the fact that cracks did not occur

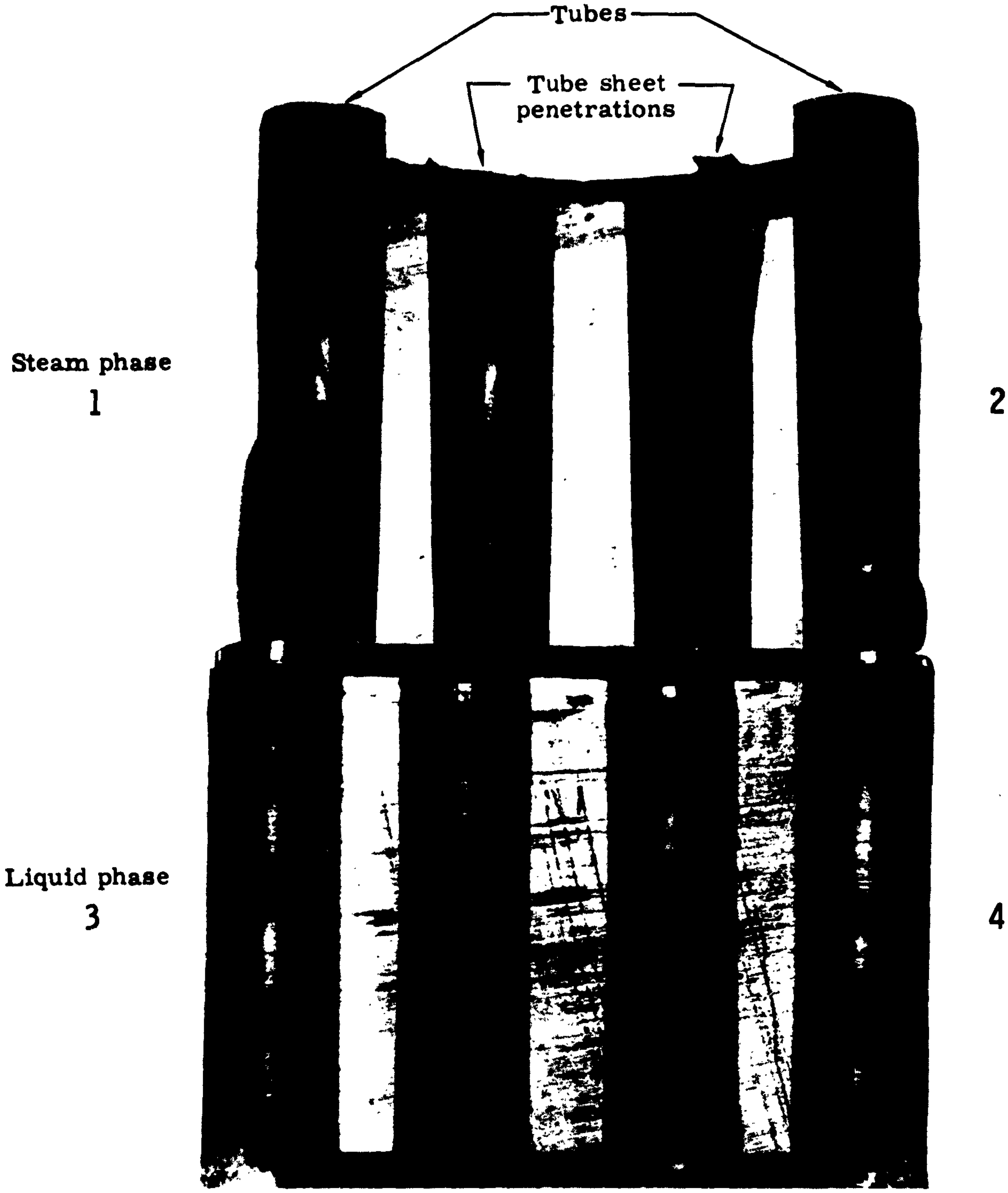


Fig. 21. MIN 15--Longitudinal Cut Through Tubes in the Tube Sheet

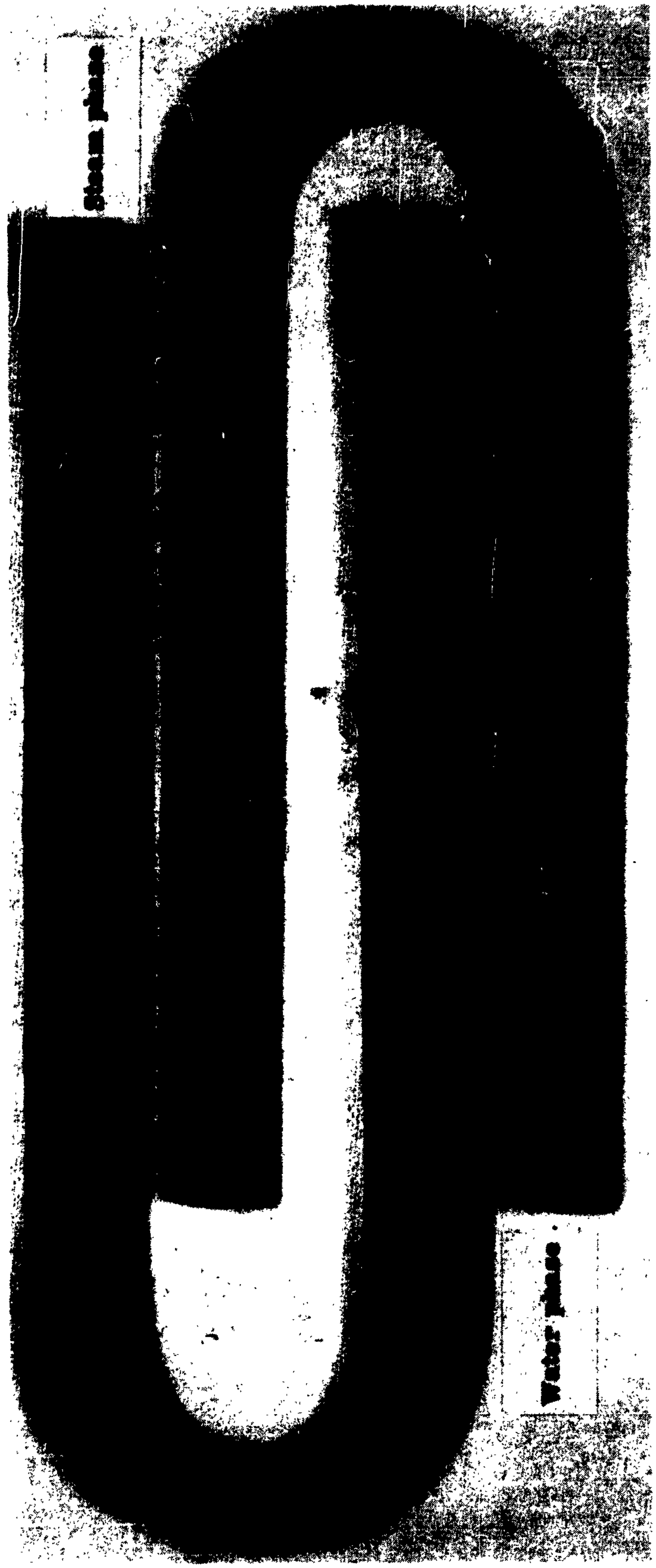


Fig. 22. MIN 15--Appearance of Bimetal Tubes After Cleaning

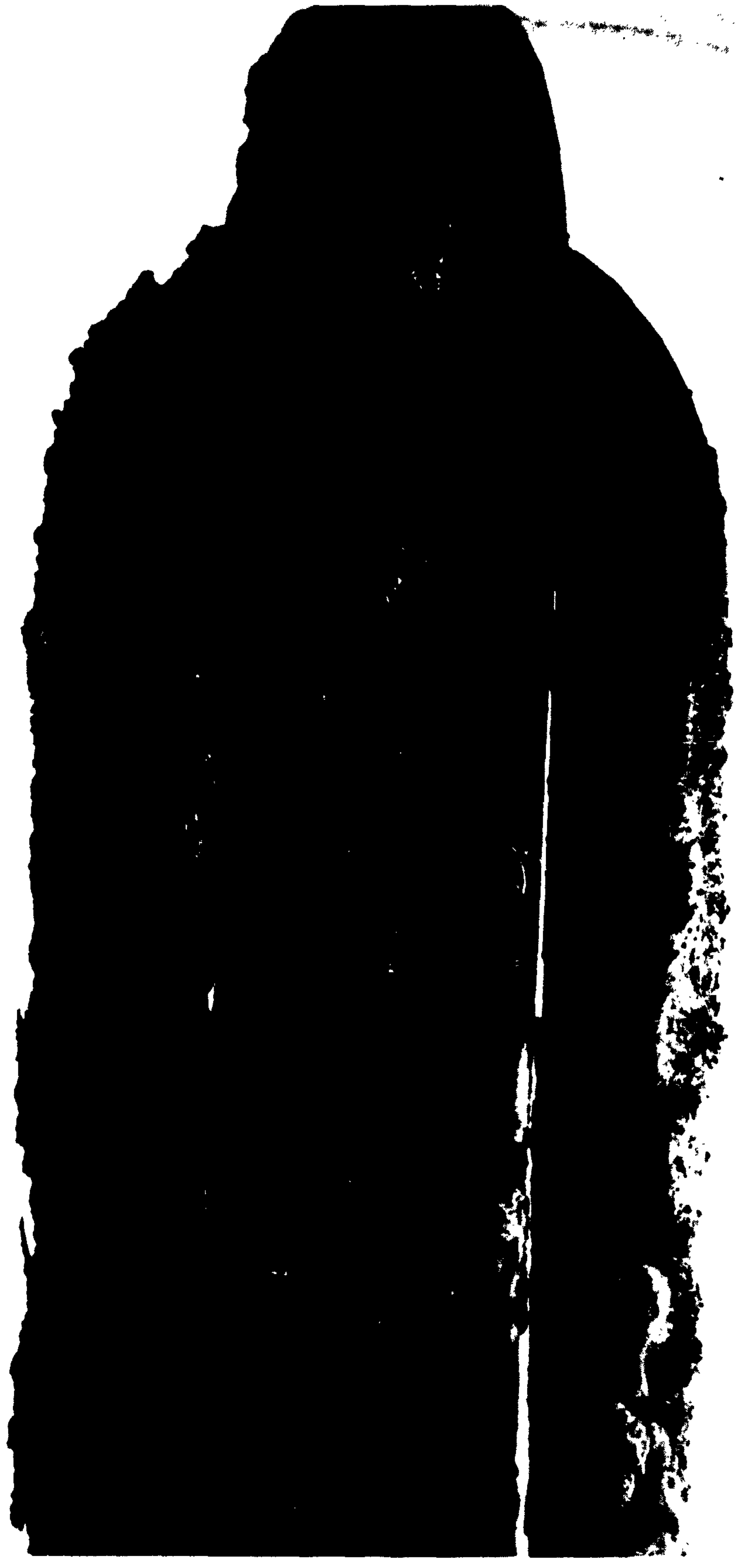


Fig. 23. MIN 16--Appearance After 3035 Hours of Testing

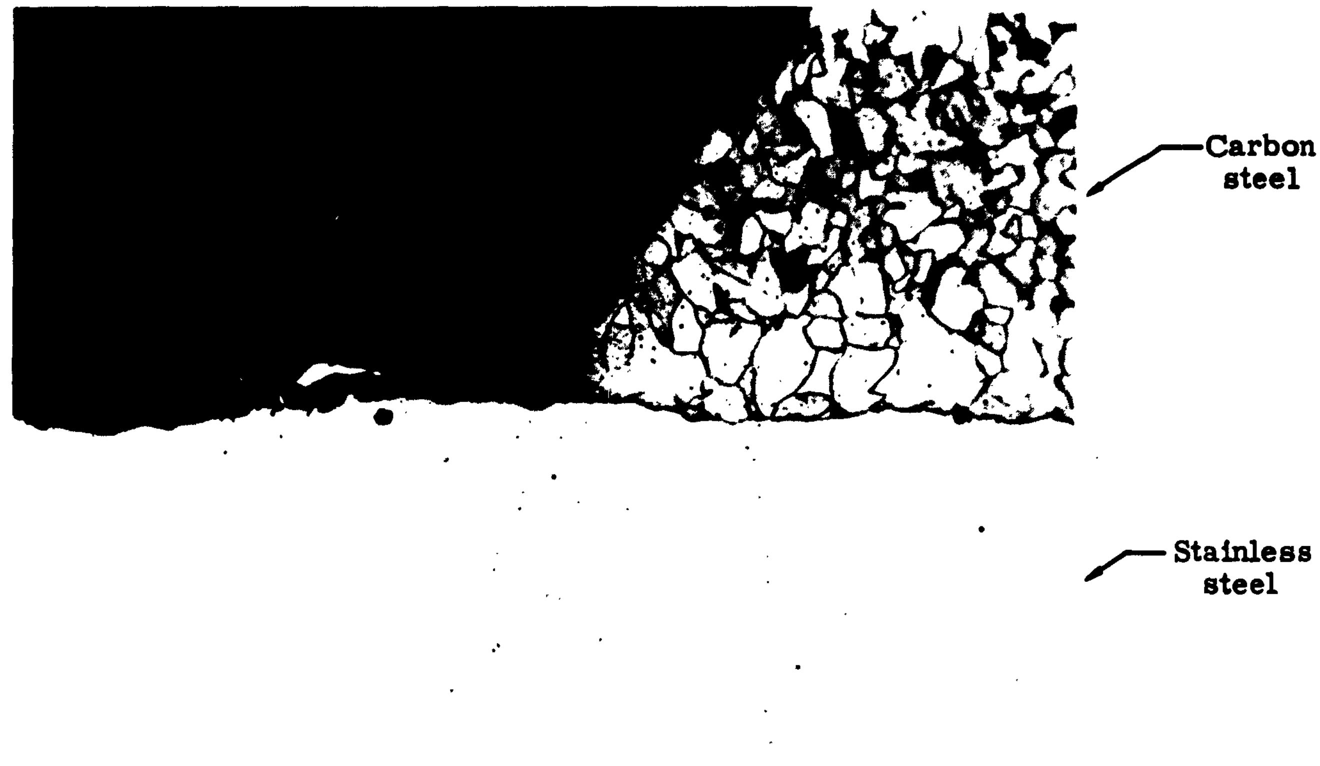
Defected area at interface

Defected area in vapor phase

Defected area in liquid phase

Fig. 24. MIN 16--Appearance After Testing and Descaling

Fig. 25. Min 16--Defect in Water Phase Before Cleaning



a. Defect in steam phase

b. Defect in water phase

Fig. 26. Photomicrographs of Defected Areas on MIN 16 Tubing (Note that the stainless steel was relatively unaffected)

in the specific area exposed is inconclusive. However, the fact that the AISI Type 304 stainless steel did not crack cannot be completely disregarded. The gross loss of the low carbon steel outer clad from the tubing in the vapor phase is no proof that cathodic protection was in effect. Considering the conditions, i.e., a nearly dry boiler scale, it is doubtful if cathodic protection could operate. It appears that further tests, designed specifically for the purpose, are required to obtain a final answer.

All of the tubes were expanded into the tube sheet in MIN 16. The environment was effectively excluded.

G. MIN 18--NICKEL

MIN 18 was tested for 1385 hours in a secondary environment containing 1000-ppm chloride; pH was adjusted to 10 with the disodium-trisodium phosphate mixture. Figure 27 shows a close up of the tubes before they were cleaned. The secondary surfaces were free of any measurable quantity of corrosion film. There was a dark gray discoloration on the tube surfaces in both vapor and liquid phases. The thin deposition on the tubes was analyzed by X-ray diffraction which showed that Fe_3O_4 was the major constituent in both the vapor and liquid phases. Emission spectroscopy showed that calcium and iron were the cations in greatest abundance. There was a very small deposit of corrosion products at the vapor-liquid interface. The submerged portions of the tubes were slightly darker than the tubes exposed to the vapor phase. In MIN 18, all of the tube-to-tube sheet joints were expanded. There was no penetration of the joints by the secondary environment.

After cleaning, the tubes appeared as shown in Fig. 28. The extent of attack was about equal to the attack on the Monel tubes in MIN 13. There was little difference in the extent of attack between the vapor and liquid phases. Pitting occurred with depths ranging up to three mils.

H. MIN 19--NICKEL

MIN 19 was tested for 1350 hours in a secondary environment containing 0.5-ppm maximum chloride, 10-ppm SO_4 and 200-ppm maximum total solids; pH was adjusted to 10 with trisodium phosphate. Figure 29 shows the tubes before cleaning. X-ray diffraction analysis showed that Fe_3O_4 was the major constituent of the very thin deposit on the tubes in both the vapor and liquid phases. Emission spectroscopy showed

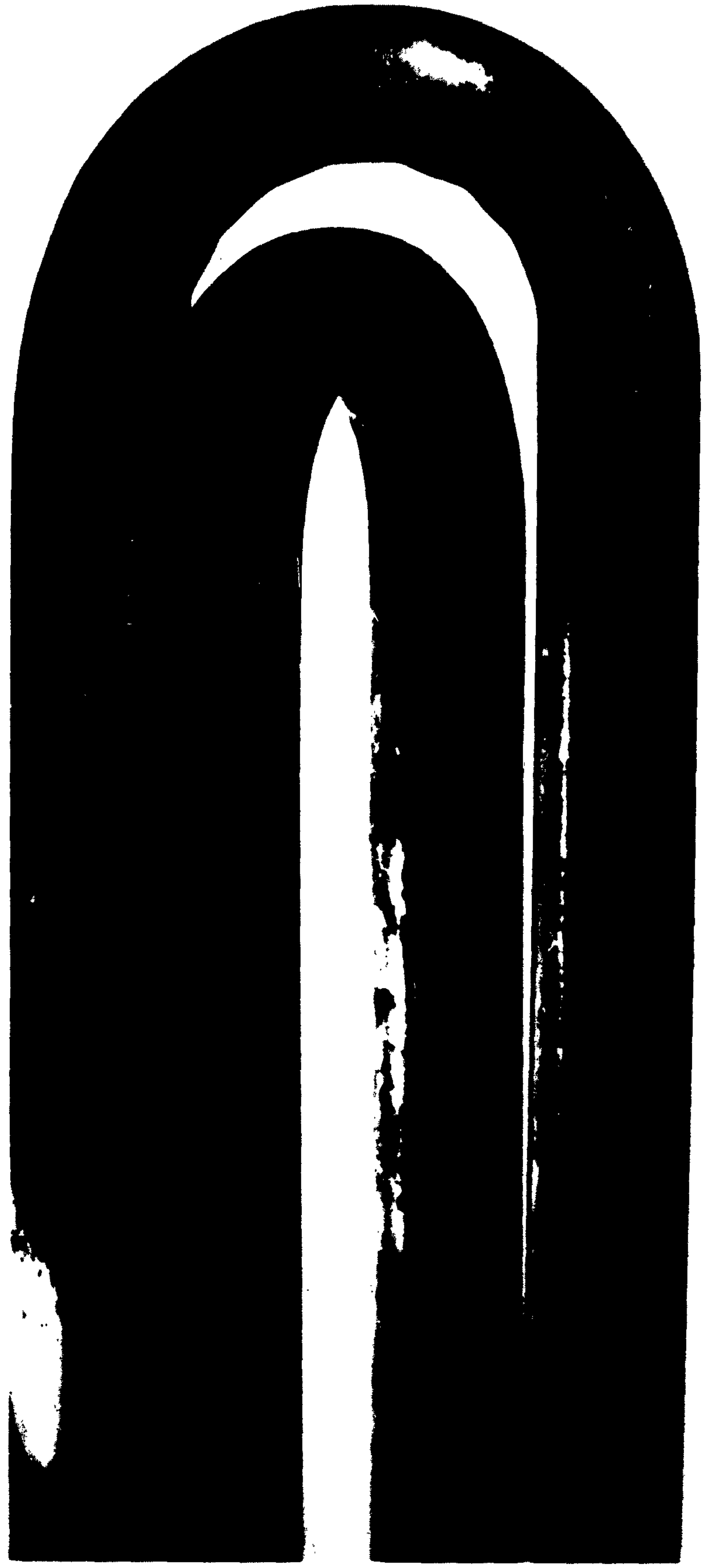


Fig. 27. Min 18--Appearance After 1385 Hours of Testing

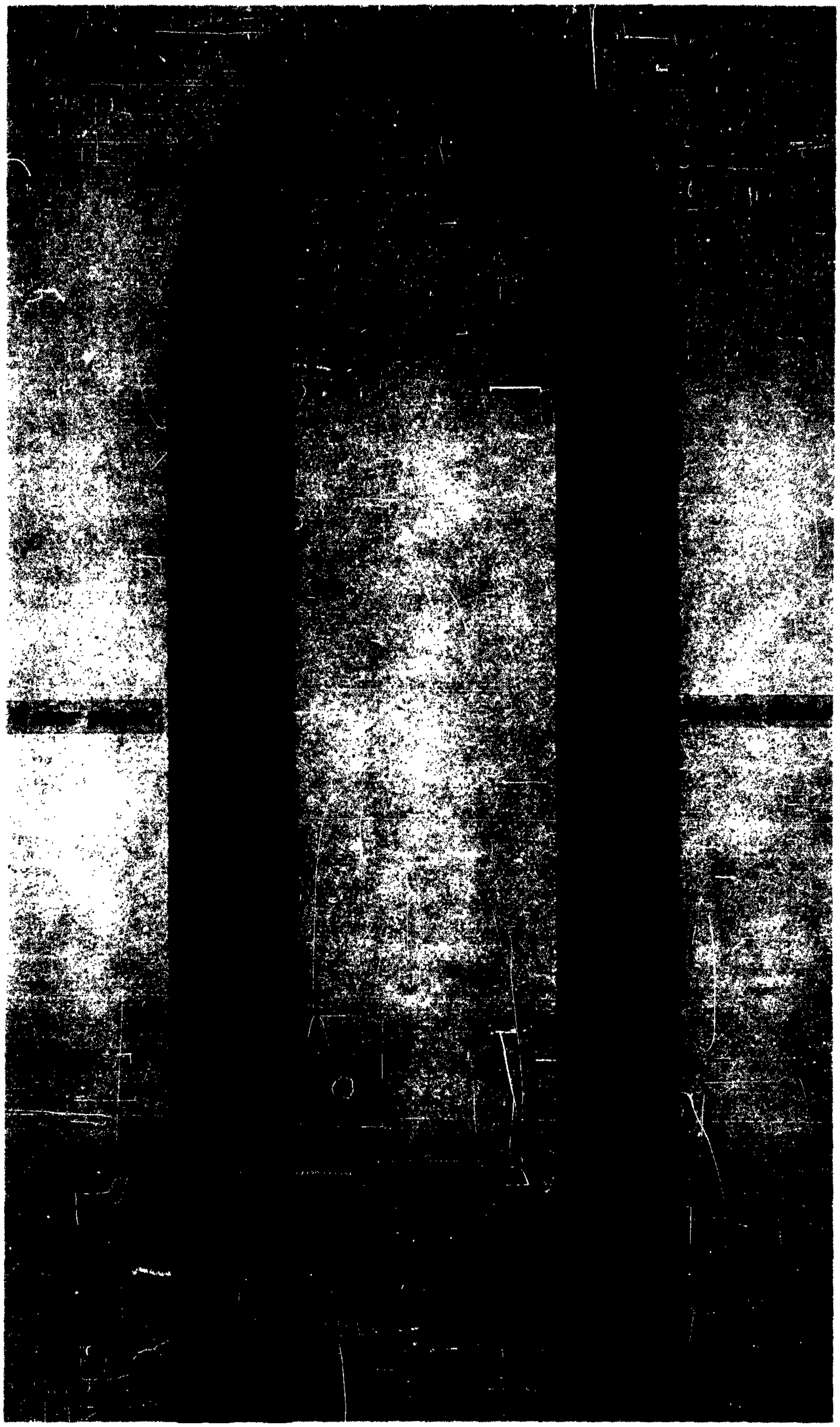


Fig. 28. Min 18--Tube After Cleaning

Fig. 29. Min 19--Appearance After 1350 Hours of Testing

that the constituents of the deposit in both the vapor and liquid phases were about the same as that found in MIN 18. The vapor-liquid interface was not as pronounced as the interface in MIN 18. Generally, the overall appearance was about the same as MIN 18. All of the tube-to-tube sheet joints were expanded in MIN 19, excluding the secondary environment.

Some incipient attack and pitting occurred in this vessel also. The extent of attack was about the same as that in MIN 18 and was comparable to that in MIN 13 and 14, the Monel test vessels. The fact that both vessels were attacked (one had 1000-ppm chloride and the other virtually no chloride) indicates that attack is not dependent upon the presence of chloride. The extent of attack was about the same in both phases.

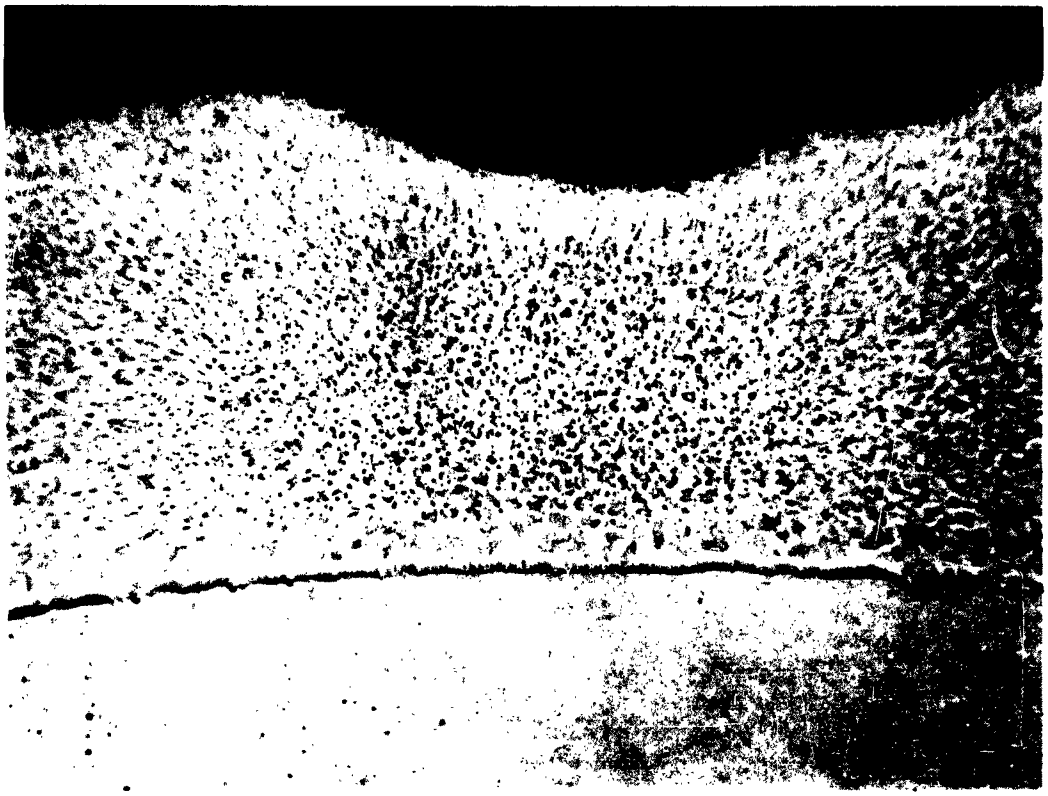
I. BIMETAL STEAM GENERATOR--SG-4

The bimetal steam generator was service tested for 4890 hours in a secondary environment containing less than 0.5-ppm chloride 10-ppm sodium sulfite and less than 200-ppm total solids; pH was adjusted to 8.5 with trisodium phosphate. Figure 30 shows the tubes and tube sheet with the secondary shell removed. The appearance of the tubes contrasts sharply with those of the bimetal steam generator tested earlier (Ref. 6). Very small amounts of corrosion products were found on the tube sheet, whereas a very large quantity was found in the vessel tested earlier.

The secondary surfaces were covered completely with a reddish brown deposit. X-ray diffraction of the material scraped from the tubes showed that the principal constituent was Fe_3O_4 with some hydrated mixed iron oxides. Emission spectroscopy showed that Fe was almost the exclusive metallic constituent of the deposit. The corrosion products at the base of the tubes on the tube sheet were found to be mixed iron oxides of about the same composition as the deposit on the tubes.

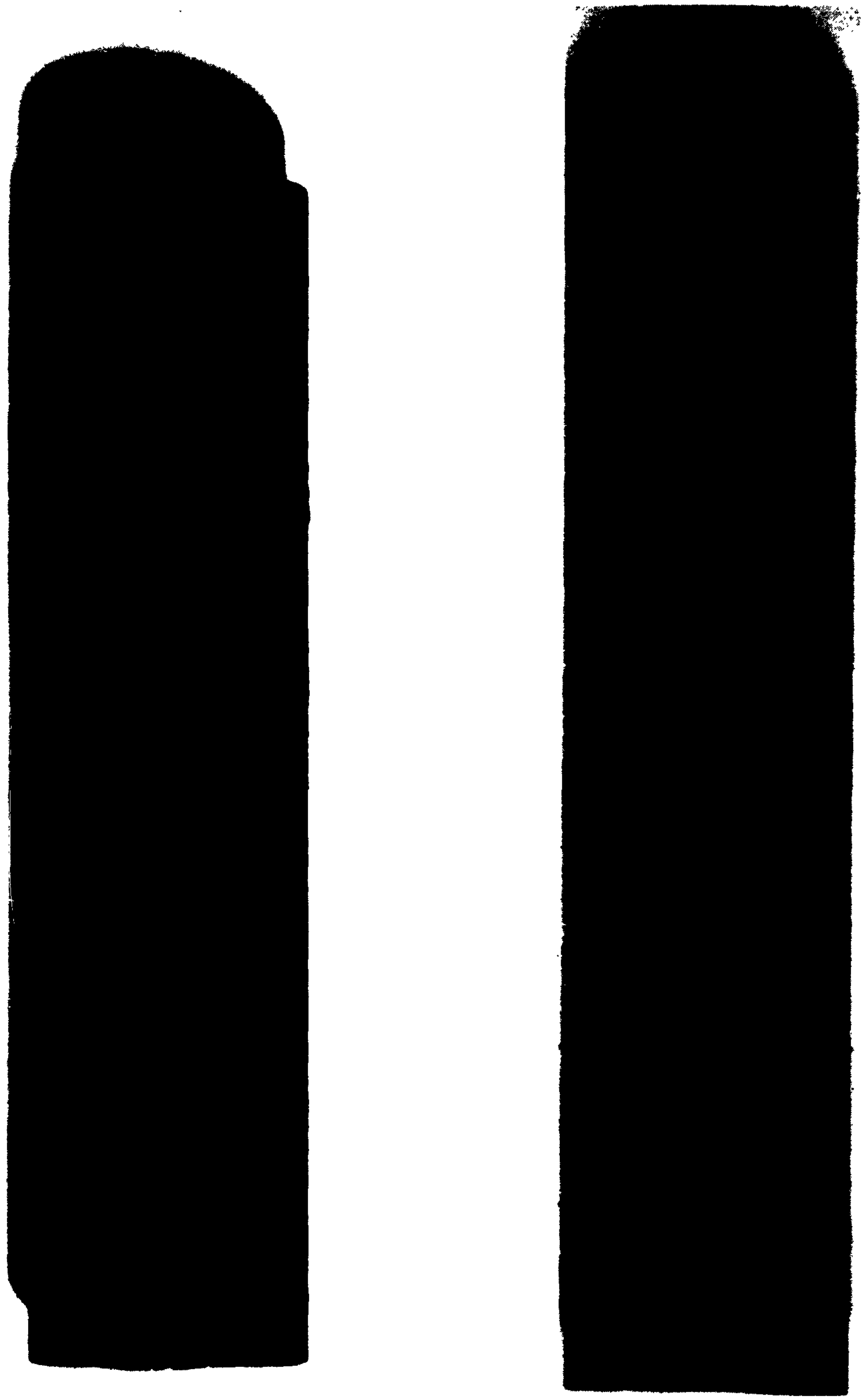
There were no full penetrations through the low carbon steel clad to the stainless steel as occurred in the bimetal steam generator tested previously. The deepest penetration found was nine mils. A photomicrograph of a typical pit is shown in Fig. 31. Figure 32 shows a portion of the tubing before and after cleaning and illustrates the extent of pitting. The extent of corrosion in the most recent test was clearly much less than that which occurred in the steam generator, SG-2. However, there was quite a difference in environments--SG-2 had 800- to 1000-ppm chloride, whereas SG-4 had, generally, less than 0.5-ppm chloride. The test times for the two are comparable. The extent of corrosion in SG-4 was somewhat more than expected, considering that the concentrations of chloride and oxygen were very low.

Fig. 30. MOD-SG-4--Appearance After 4890 Hours of Testing



Magnification 75X.

Fig. 31. Photomicrograph of Pit in SG-4 Tubing; 0.0075-Inch Depth



a. Before cleaning b. After cleaning

Fig. 32. Appearance of SG-4 Bimetal Tubing

The tubes of this vessel were expanded into the tube sheet. There was no penetration of the crevice by the secondary environment.

J. BIMETAL SUPERHEATER--SH-4

The superheater was service tested for 4890 hours along with the bimetal steam generator. The appearance of the superheater, after removal of the shell, is shown in Fig. 33. The tubes were covered with an adherent reddish brown deposit. X-ray diffraction analysis showed two principal patterns, Fe_2O_3 and Fe_3O_4, in the corrosion products. Emission spectroscopy showed the principal component to be Fe. There was a slightly greater quantity of corrosion products on the tube sheet of the superheater than on the steam generator. X-ray diffraction analysis showed that the corrosion product on the tube sheet had the same composition as the deposit on the tubes.

The tubes of this vessel were expanded into the tube sheet. There was no penetration of the crevice by the secondary environment. Just as the steam generator from this set was not nearly as corroded as the steam generator from the previously tested set, so the superheater was not nearly as corroded as the one tested earlier. The deepest pit found in the surface of the secondary tubing was only 3.5 mils. Pitting was more severe on the tubes near the tube sheet.

K. INCONEL STEAM GENERATOR--SG-7

This vessel was service tested for 4747 hours in a secondary environment containing less than 0.5 ppm chloride, 10 ppm sodium sulfite and 150 ppm PO_4 added as trisodium phosphate; pH was 10 to 10.5. Figure 34 shows the tubes with the secondary shell removed. The tubes were covered with a thin, adherent, reddish brown deposit which X-ray diffraction analysis identified as mixed iron oxides, mostly Fe_2O_3. After cleaning, the tubes appeared as shown in Fig. 35.

The agglomerate of corrosion products on the tube sheet at the base of the tubes had the same composition as the coating on the tubes except for a minor inclusion of $CaCO_3$. No corrosion products were found in the crevice between the expanded tube and the tube sheet.

No cracks or pits were found on any of the secondary surfaces of the Inconel tubing.

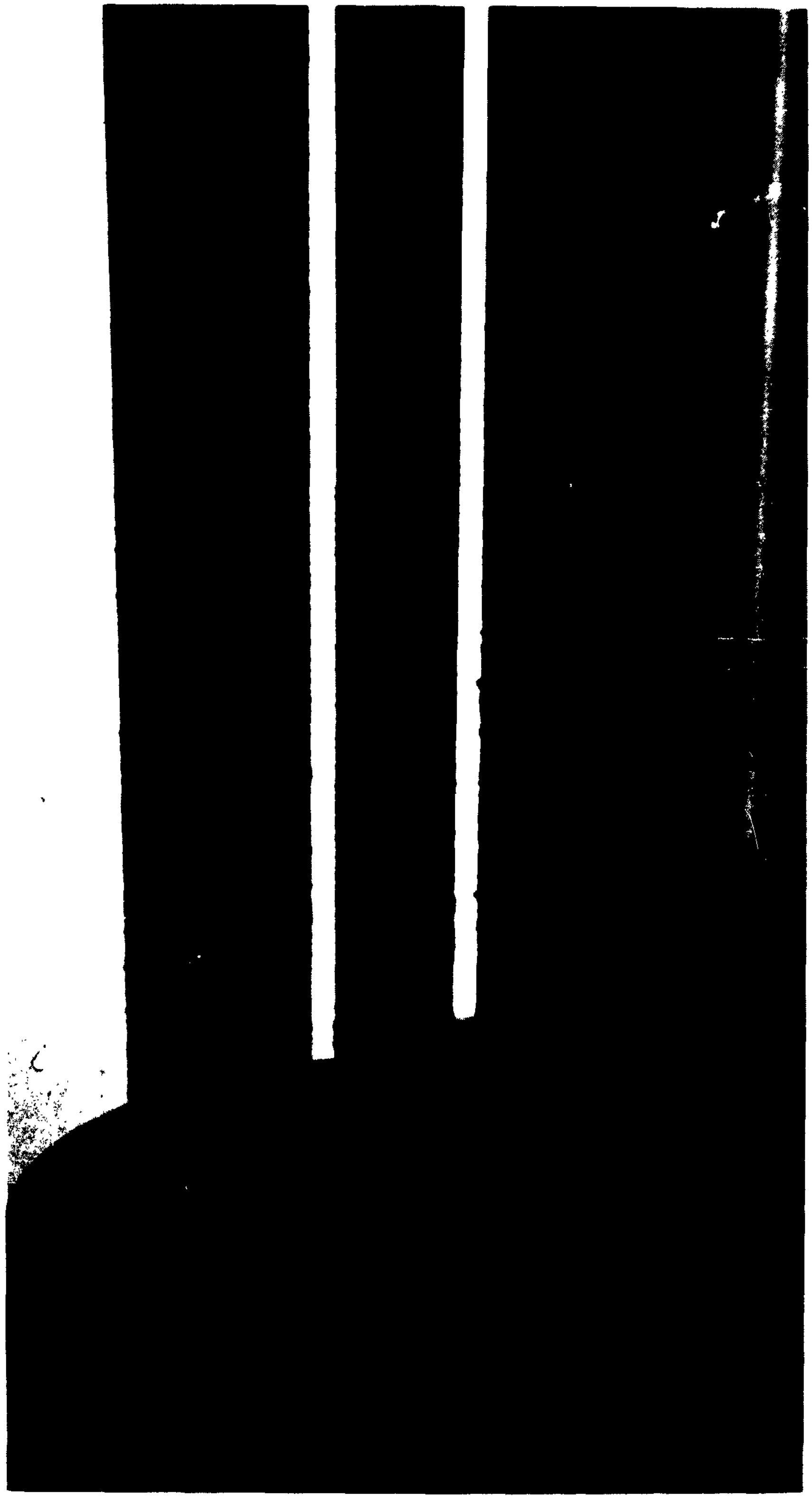


Fig. 33. MOD-SH-4--Appearance after 4890 Hours of Testing

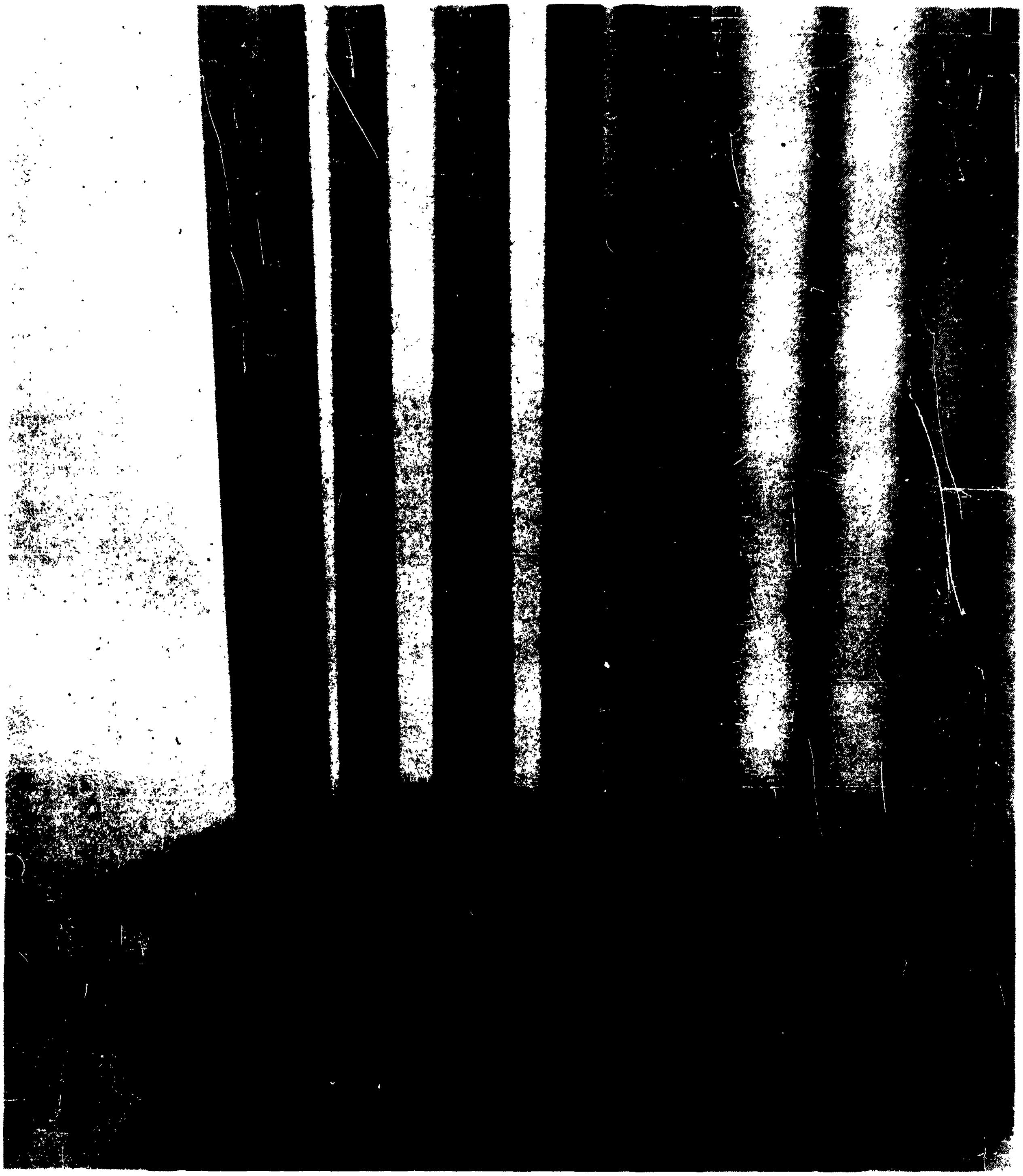


Fig. 34. MOD-SG-7--Appearance After 4747 Hours of Testing

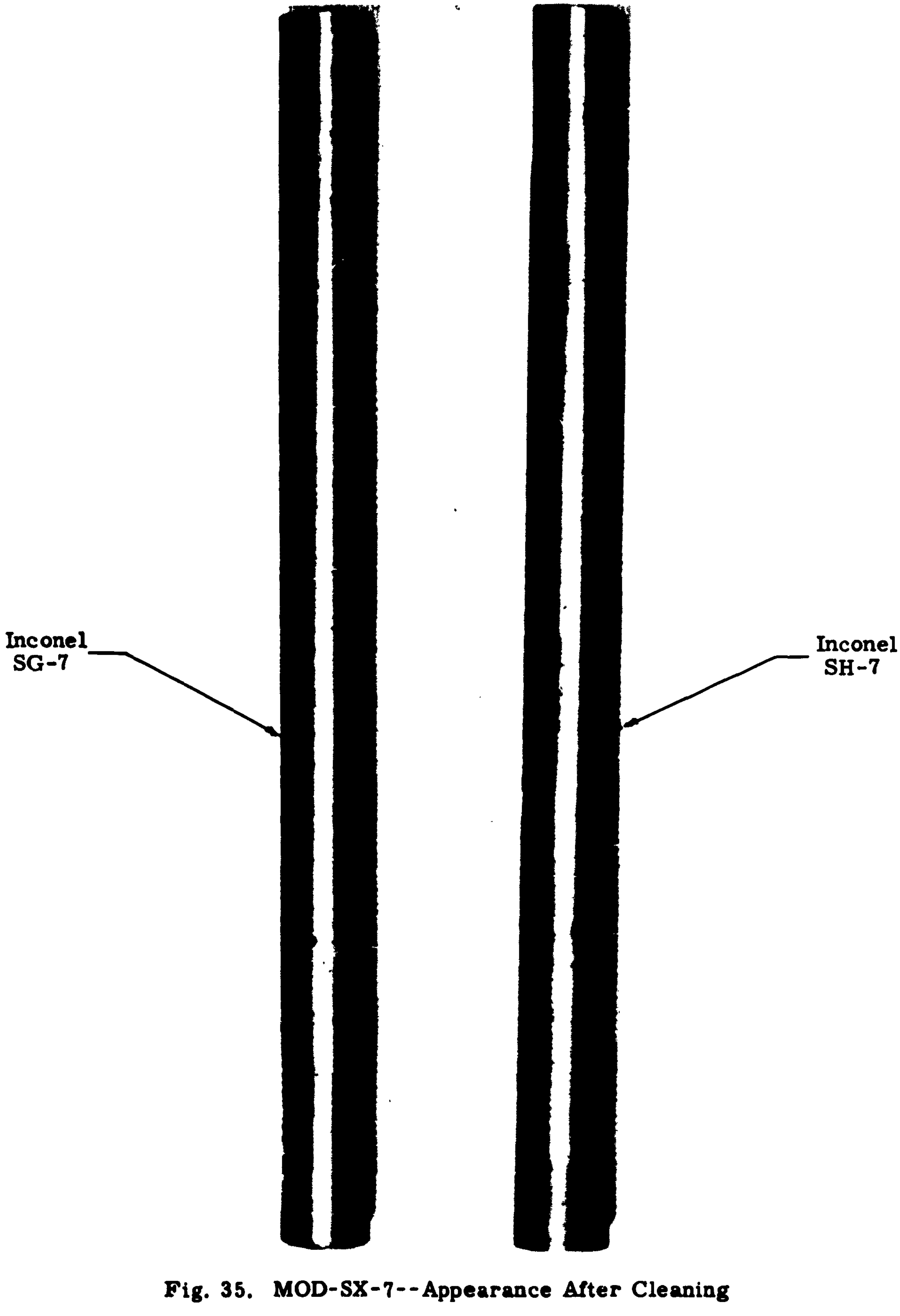


Fig. 35. MOD-SX-7--Appearance After Cleaning

L. INCONEL SUPERHEATER--SH-7

The superheater was tested for 4747 hours along with the steam generator. The tubes appeared as shown in Fig. 36, after the secondary shell was removed. The tubes were covered with a loosely attached, pale, reddish brown film very similar in appearance to the film on the tubes in the Inconel steam generator, SG-7. The principal constituents were identified as Fe_3O_4 and Fe_2O_3 by X-ray diffraction analysis. Emission spectroscopy showed that the metallic constituents were almost exclusively Fe. After cleaning, the tubes appeared as shown in Fig. 35. No cracks or pits were found in any of the Inconel tubing.

There was no environmental penetration of the crevice between the expanded tube and the tube sheet.

Fig. 36. MOD-SH-7--Appearance After 4747 Hours of Testing

VIII. CONCLUSIONS

Several conclusions are obvious, based on the results of the tests covered in this report. The most important conclusion is that Inconel was the material which performed best. The Inconel tubes in the steam generator and the superheater which were tested in reactor quality water were almost completely unaffected by the environment. Even when exposed to water which contained a high concentration of dissolved chloride, Inconel showed a resistance superior to all other materials tested. This is especially evident when it is recalled that the Inconel miniature vessels were tested more than twice as long as the corresponding Monel and nickel vessels.

Both Monel and nickel pitted whether exposed to an environment which contained a high concentration of dissolved chloride or a reactor quality water. Both metals were attacked more by the environment which contained chloride than by the reactor grade water. Also, and this is true of all materials tested, in those cases where attack occurred, the attack was somewhat more aggressive in the vapor phase than in the liquid phase.

The low carbon steel was far superior in reactor quality water than in water which contained a high concentration of dissolved chloride. However, even in reactor quality water the rate of penetration was prohibitive. The hypothesis of cathodic protection of the stainless steel cladding by the carbon steel was further supported by the MIN 16 results. Complete verification would, however, require more extensive tests.

There was very limited, if any, penetration of crevices formed by tubes which had been expanded into the tube sheet, whereas there was always penetration in the crevices where tubes were not expanded. In the vapor phase, the penetration always continued to the seal weld of the tube-to-tube sheet. None of the seal welds or their attendant heat affected zones were affected.

IX. REFERENCES

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2. "Autoclave Testing of Type 430 Stainless Steel," MND-E-1602, The Martin Company.

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7. "Corrosion Testing of Inconel and Croloy 16-1 Heat Exchangers," MND-E-2326, March 1960.

8. "Martin-ANPP Corrosion Testing Program--Methods and Procedures," MND-E-2145, February 1961.

9. Whirl, S. F., and Purcell, T. E., "Proceedings of the Third Annual Water Conference," Engineers Society of Western Pennsylvania, 1942.

APPENDIX A

Calendar of Loop Testing

Loop Vessel Designation	November						
			1	2	3	4	5
1 Model				22.2	24.0	24.0	1.5
2 Model				22.2	24.0	24.0	1.5
1 Miniature				11.5	24.0	24.0	1.5
2 Miniature				17.3	24.0	24.0	1.5
3 Miniature				17.3	24.0	24.0	1.5
4 Miniature				17.3	24.0	24.0	1.5
	6	7	8	9	10	11	12
1 Model	0.0	0.0	0.0	0.0	20.2	1.0	0.0
2 Model	0.0	0.0	0.0	0.0	20.2	1.0	0.0
1 Miniature	0.0	0.0	0.0	0.0	15.5	1.0	0.0
2 Miniature	0.0	0.0	0.0	0.0	15.5	1.0	0.0
3 Miniature	0.0	0.0	0.0	0.0	15.5	1.0	0.0
4 Miniature	0.0	0.0	0.0	0.0	15.5	1.0	0.0
	13	14	15	16	17	18	19
1 Model	0.0	0.0	12.2	1.0	11.2	0.0	0.0
2 Model	0.0	0.0	12.2	1.0	6.2	0.0	0.0
1 Miniature	0.0	0.0	10.2	1.0	11.2	0.0	0.0
2 Miniature	0.0	0.0	10.2	1.0	11.2	0.0	0.0
3 Miniature	0.0	0.0	10.2	1.0	11.2	0.0	0.0
4 Miniature	0.0	0.0	10.2	1.0	11.2	0.0	0.0
	20	21	22	23	24	25	26
1 Model	0.0	21.8	21.0	14.4	0.0	2.2	0.0
2 Model	0.0	21.5	21.0	14.4	0.0	2.2	0.0
1 Miniature	0.0	21.5	21.0	14.3	0.0	2.2	0.0
2 Miniature	0.0	18.5	21.0	14.3	0.0	2.2	0.0
3 Miniature	0.0	21.5	21.0	14.3	0.0	2.2	0.0
4 Miniature	0.0	21.5	21.0	14.3	0.0	2.2	0.0
	27	28	29	30			
1 Model	0.0	0.0	22.0	24.0			
2 Model	0.0	0.0	22.5	24.0			
1 Miniature	0.0	0.0	22.5	24.0			
2 Miniature	0.0	0.0	22.5	24.0			
3 Miniature	0.0	0.0	22.5	24.0			
4 Miniature	0.0	0.0	22.5	24.0			

1 Model	MOD SG-4 and SH-4	222.7 hours*
2 Model	MOD SG-7 and SH-7	217.9 hours*
1 Miniature	MIN 10	205.4 hours*
2 Miniature	MIN 15	208.2 hours*
3 Miniature	MIN 11	211.2 hours*
4 Miniature	MIN 16	211.2 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

***Total hours test time to November 30, 1960**

Loop Vessel Designation	December						
					1	2	3
1 Model					24.0	11.0	22.3
2 Model					24.0	11.0	22.3
1 Miniature					24.0	11.0	22.3
2 Miniature					24.0	11.0	22.3
3 Miniature					24.0	11.0	22.3
4 Miniature					24.0	11.0	22.3
	4	5	6	7	8	9	10
1 Model	24.0	7.4	3.0				
2 Model	24.0	24.0	3.0				
1 Miniature	17.8	19.5	3.0				
2 Miniature	17.8	19.5	3.0				
3 Miniature	17.8	2.5	3.0				
4 Miniature	17.8	19.5	3.0				
	11	12	13	14	15	16	17
1 Model							
2 Model							
1 Miniature							
2 Miniature		Major loop overhaul					
3 Miniature							
4 Miniature							
	18	19	20	21	22	23	24
1 Model		5.7	24.0	24.0	22.8	24.0	24.0
2 Model		19.2	24.0	24.0	23.4	24.0	24.0
1 Miniature		19.2	24.0	24.0	24.0	24.0	24.0
2 Miniature		19.2	24.0	24.0	24.0	24.0	24.0
3 Miniature		19.2	24.0	24.0	24.0	24.0	24.0
4 Miniature		19.2	24.0	24.0	24.0	24.0	24.0
	25	26	27	28	29	30	31
1 Model	24.0	24.0	6.1	19.0	24.0	24.0	24.0
2 Model	24.0	24.0	6.3	19.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	6.0	17.0	24.0	24.0	24.0
2 Miniature	24.0	24.0	6.3	17.0	24.0	24.0	24.0
3 Miniature	24.0	24.0	5.8	16.0	24.0	24.0	24.0
4 Miniature	24.0	24.0	6.3	17.0	24.0	24.0	24.0

1 Model	MOD SG-4 and SH-4	584.0 hours*
2 Model	MOD SG-7 and SH-7	610.1 hours*
1 Miniature	MIN 10	585.2 hours*
2 Miniature	MIN 15	588.3 hours*
3 Miniature	MIN 11	572.8 hours*
4 Miniature	MIN 16	572.8 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours test time to December 31, 1961

Loop Vessel Designation	January						
	1	2	3	4	5	6	7
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	5.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	0.5	0.0	23.5	24.0	24.0	24.0	24.0
2 Miniature	0.5	0.0	23.5	24.0	24.0	24.0	24.0
3 Miniature	0.5	0.0	23.5	24.0	24.0	24.0	24.0
4 Miniature	0.5	0.0	23.5	24.0	24.0	24.0	24.0
	8	9	10	11	12	13	14
1 Model	0.0	18.0	24.0	24.0	24.0	24.0	24.0
2 Model	21.0	15.3	24.0	24.0	24.0	24.0	24.0
1 Miniature	21.0	17.5	24.0	24.0	24.0	24.0	24.0
2 Miniature	21.0	17.5	24.0	24.0	24.0	24.0	24.0
3 Miniature	21.0	15.5	24.0	24.0	24.0	24.0	24.0
4 Miniature	21.0	18.3	24.0	24.0	24.0	24.0	24.0
	15	16	17	18	19	20	21
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	20.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Miniature	24.0	24.0	21.0	24.0	24.0	24.0	24.0
3 Miniature	24.0	24.0	24.0	22.2	24.0	24.0	24.0
4 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	22	23	24	25	26	27	28
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	15.5	18.5	24.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	21.5	24.0	24.0	24.0	24.0
2 Miniature	24.0	24.0	24.0	24.0	24.0	21.5	24.0
3 Miniature	24.0	24.0	24.0	24.0	24.0	21.7	24.0
4 Miniature	24.0	24.0	24.0	24.0	24.0	21.9	24.0
	29	30	31				
1 Model	24.0	24.0	24.0				
2 Model	24.0	24.0	24.0				
1 Miniature	24.0	24.0	24.0				
2 Miniature	24.0	24.0	24.0				
3 Miniature	24.0	24.0	24.0				
4 Miniature	24.0	24.0	24.0				

1 Model	MOD SG-4 and SH-4	1279.0 hours*
2 Model	MOD SG-7 and SH-7	1324.4 hours*
1 Miniature	MIN 10	1269.2 hours*
2 Miniature	MIN 15	1269.3 hours*
3 Miniature	MIN 11	1253.2 hours*
4 Miniature	MIN 16	1258.0 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours test time to January 31, 1961

Loop Vessel Designation	February						
				1	2	3	4
1 Model				24.0	24.0	22.0	
2 Model				24.0	24.0	22.0	
1 Miniature				24.0	24.0	22.0	
2 Miniature				24.0	10.0	22.0	
3 Miniature				24.0	24.0	22.0	
4 Miniature				24.0	24.0	22.0	
	5	6	7	8	9	10	11
1 Model	50-kw heater electrical terminal failure; line pump impeller replaced					21.0	24.0
2 Model						21.0	24.0
1 Miniature						21.0	24.0
2 Miniature						21.0	24.0
3 Miniature						21.0	24.0
4 Miniature						21.0	24.0
	12	13	14	15	16	17	18
1 Model	12.0	23.0	24.0	24.0	24.0	18.1	24.0
2 Model	12.0	23.0	24.0	24.0	24.0	18.1	24.0
1 Miniature	12.0	23.0	24.0	24.0	24.0	18.1	24.0
2 Miniature	12.0	23.0	24.0	24.0	24.0	18.1	24.0
3 Miniature	12.0	23.0	24.0	24.0	24.0	18.1	24.0
4 Miniature	12.0	23.0	24.0	24.0	24.0	18.1	24.0
	19	20	21	22	23	24	25
1 Model	24.0	24.0	24.0	24.0	24.0	17.8	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	0.0	0.0
1 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
3 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
4 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	24.0
	26	27	28				
1 Model	24.0	24.0	24.0				
2 Model	0.0	24.0	24.0				
1 Miniature	24.0	24.0	24.0				
2 Miniature	24.0	24.0	24.0				
3 Miniature	24.0	24.0	24.0				
4 Miniature	24.0	24.0	24.0				

1 Model	MOD SG-4 and SH-4	1776.9 hours*
2 Model	MOD SG-7 and SH-7	1756.5 hours*
1 Miniature	MIN 10	1773.3 hours*
2 Miniature	MIN 15	1759.4 hours*
3 Miniature	MIN 11	1757.3 hours*
4 Miniature	MIN 16	1762.1 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

***Total hours of test to February 28, 1961**

Loop Vessel Designation	March						
				1	2	3	4
1 Model				24.0	24.0	24.0	24.0
2 Model				8.0	24.0	15.0	0.0
1 Miniature				21.9	24.0	24.0	24.0
2 Miniature				21.9	24.0	24.0	24.0
3 Miniature				21.9	24.0	24.0	24.0
4 Miniature				21.9	24.0	24.0	24.0
	5	6	7	8	9	10	11
1 Model	2.0	22.8	24.0	24.0	24.0	24.0	21.0
2 Model	0.0	22.8	24.0	24.0	24.0	18.0	0.0
1 Miniature	2.0	22.8	24.0	24.0	24.0	24.0	21.0
2 Miniature	2.0	22.8	24.0	24.0	24.0	24.0	21.0
3 Miniature	2.0	22.8	24.0	24.0	24.0	24.0	17.0
4 Miniature	2.0	22.8	24.0	24.0	24.0	24.0	22.0
	12	13	14	15	16	17	18
1 Model	0.0	2.5	17.0	21.8	24.0	24.0	23.0
2 Model	0.0	22.0	17.0	23.4	22.8	24.0	24.0
1 Miniature	0.0	22.0	17.0	24.0	24.0	24.0	24.0
2 Miniature	0.0	22.0	17.0	24.0	24.0	24.0	24.0
3 Miniature	0.0	22.0	17.0	24.0	24.0	24.0	24.0
4 Miniature	0.0	22.0	17.0	24.0	24.0	24.0	24.0
	19	20	21	22	23	24	25
1 Model	0.0	22.0	24.0	24.0	24.0	24.0	24.0
2 Model	3.0	22.0	22.5	20.3	17.0	24.0	24.0
1 Miniature	3.0	22.0	24.0	24.0	24.0	24.0	24.0
2 Miniature	3.0	22.0	24.0	24.0	24.0	24.0	24.0
3 Miniature	3.0	22.0	24.0	24.0	24.0	24.0	24.0
4 Miniature	4.5	22.0	24.0	24.0	24.0	24.0	24.0
	26	27	28	29	30	31	
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	
2 Model	24.0	24.0	24.0	5.8	24.0	24.0	
1 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	
2 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	
3 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	
4 Miniature	24.0	24.0	24.0	24.0	24.0	24.0	

1 Model	MOD SG-4 and SH-4	2413.0 hours*
2 Model	MOD SG-7 and SH-7	2308.3 hours*
1 Miniature	MIN 10	2433.0 hours*
2 Miniature	MIN 15	2419.1 hours*
3 Miniature	MIN 11	2413.0 hours*
4 Miniature	MIN 16	2424.3 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

***Total hours of test time for March 31, 1961**

Loop Vessel Designation	April						
							1
1 Model							24.0
2 Model							24.0
1 Miniature							24.0
2 Miniature							24.0
3 Miniature							24.0
4 Miniature							24.0
	2	3	4	5	6	7	8
1 Model	0.0	22.0	24.0	24.0	24.0	20.5	0.0
2 Model	0.0	22.0	24.0	24.0	24.0	20.5	0.0
1 Miniature	0.0	22.0	24.0	24.0	24.0	20.5	0.0
2 Miniature	0.0	22.0	24.0	24.0	24.0	20.5	0.0
3 Miniature	0.0	22.0	24.0	24.0	24.0	20.5	0.0
4 Miniature	0.0	22.0	24.0	24.0	24.0	20.5	0.0
	9	10	11	12	13	14	15
1 Model	0.0	1.2	0.0	9.6	24.0	14.2	0.0
2 Model	0.0	1.2	0.0	9.6	24.0	11.2	0.0
1 Miniature	0.0	1.2	0.0	9.5	24.0	14.7	0.0
2 Miniature	0.0	1.2	0.0	9.5	24.0	13.6	0.0
3 Miniature	0.0	1.2	0.0	9.5	24.0	14.7	0.0
4 Miniature	0.0	1.2	0.0	9.5	24.0	13.7	0.0
	16	17	18	19	20	21	22
1 Model	0.0	21.8	24.0	24.0	24.0	19.5	1.5
2 Model	0.0	21.8	24.0	24.0	24.0	3.0	0.0
1 Miniature	0.0	23.0	24.0	24.0	24.0	21.2	4.5
2 Miniature	0.0	23.0	24.0	24.0	24.0	21.5	4.0
3 Miniature	0.0	23.0	24.0	24.0	24.0	21.2	4.3
4 Miniature	0.0	23.0	24.0	24.0	24.0	21.5	4.2
	23	24	25	26	27	28	29
1 Model	0.0	20.0	24.0	24.0	24.0	24.0	14.5
2 Model	0.0	20.0	24.0	24.0	24.0	24.0	14.2
1 Miniature	0.0	20.0	24.0	24.0	24.0	24.0	14.6
2 Miniature	0.0	20.0	24.0	24.0	24.0	24.0	14.5
3 Miniature	0.0	20.0	24.0	24.0	24.0	24.0	14.5
4 Miniature	0.0	20.0	24.0	24.0	24.0	24.0	14.5
	30						
1 Model	0.0	1 Model	MOD SG-4 and SH-4			2845.8 hours*	
2 Model	0.0	2 Model	MOD SG-7 and SH-7			2714.1 hours*	
1 Miniature	0.0	1 Miniature	MIN 10			2872.2 hours*	
2 Miniature	0.0	2 Miniature	MIN 15			2854.4 hours*	
3 Miniature	0.0	3 Miniature	MIN 11			2850.9 hours*	
4 Miniature	0.0	4 Miniature	MIN 16			2861.4 hours*	

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours test time to April 30, 1961.

Loop Vessel Designation	May						
		1	2	3	4	5	6
1 Model		21.2	24.0	24.0	24.0	24.0	24.0
2 Model		21.5	24.0	24.0	24.0	24.0	24.0
1 Miniature		20.5	24.0	24.0	24.0	24.0	24.0
2 Miniature		20.7	24.0	24.0	24.0	20.5	24.0
3 Miniature		20.5	24.0	24.0	24.0	24.0	24.0
4 Miniature		20.7	24.0	24.0	24.0	24.0	24.0
	7	8	9	10	11	12	13
1 Model	24.0	7.2	Primary circulating pump overhaul		23.5	24.0	24.0
2 Model	24.0	7.2			23.7	24.0	24.0
1 Miniature	24.0	8.0					
2 Miniature	24.0	8.2					
3 Miniature	24.0	8.2					
4 Miniature	24.0	8.2					
	14	15	16	17	18	19	20
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	23.1
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	23.2
1 Miniature		Installation of second series of miniature vessels					
2 Miniature							
3 Miniature							
4 Miniature							
	21	22	23	24	25	26	27
1 Model	0.0	22.0	24.0	24.0	24.0	24.0	24.0
2 Model	0.0	20.5	24.0	24.0	24.0	24.0	24.0
1 Miniature						17.4	24.0
2 Miniature							
3 Miniature						17.4	24.0
4 Miniature						17.4	24.0
	28	29	30	31			
1 Model	11.3	19.5	24.0	24.0			
2 Model	3.4	18.5	24.0	24.0			
1 Miniature	5.8	19.0	24.0	24.0			
2 Miniature		17.0	24.0	17.0			
3 Miniature	5.8	19.0	24.0	24.0			
4 Miniature	5.8	19.0	24.0	24.0			

1 Model MOD SG-4 and SH-4 3478.1 hours*
2 Model MOD SG-7 and SH-7 3336.1 hours*
1 Miniature MIN 10-3044.7 hours**----MIN 18-114.2 hours***
2 Miniature MIN 15-3018.8 hours**----MIN 13- 58.0 hours***
3 Miniature MIN 11-3023.6 hours**----MIN 19-114.2 hours****
4 Miniature MIN 16-3035.3 hours**----MIN 14-114.2 hours***

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours test time to May 31, 1961
**Total hours service time on vessel. Test terminated May 8, 1961
***MIN 18, 19 and 14 in service May 26, 1961
****MIN 13 in service May 29, 1961

Loop Vessel Designation	June						
					1	2	3
1 Model					24.0	24.0	24.0
2 Model					24.0	24.0	24.0
1 Miniature					24.0	24.0	24.0
2 Miniature					24.0	24.0	3.6
3 Miniature					24.0	18.7	0.0
4 Miniature					24.0	24.0	6.6
	4	5	6	7	8	9	10
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	0.0	14.0	15.1	20.5	24.0	24.0	0.0
2 Miniature	0.0	24.0	24.0	24.0	24.0	24.0	24.0
3 Miniature	0.0	24.0	24.0	22.5	24.0	24.0	2.5
4 Miniature	0.0	24.0	24.0	24.0	24.0	24.0	14.7
	11	12	13	14	15	16	17
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	0.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Miniature	0.0	24.0	24.0	24.0	24.0	24.0	24.0
3 Miniature	0.0	24.0	24.0	21.8	24.0	24.0	24.0
4 Miniature	0.0	24.0	24.0	24.0	24.0	24.0	24.0
	18	19	20	21	22	23	24
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	22.9	24.0	24.0
1 Miniature	24.0	24.0	21.2	20.0	24.0	24.0	4.0
2 Miniature	24.0	24.0	22.2	24.0	24.0	24.0	24.0
3 Miniature	24.0	24.0	14.4	24.0	24.0	24.0	5.7
4 Miniature	24.0	24.0	21.9	24.0	24.0	24.0	16.4
	25	26	27	28	29	30	
1 Model	13.6	Prim.	20.0	24.0	24.0	24.0	
2 Model	13.6	circ	20.0	24.0	24.0	24.0	
1 Miniature	0.0	pump	20.0	24.0	24.0	24.0	
2 Miniature	14.0	over-	20.0	24.0	24.0	24.0	
3 Miniature	0.0	haul	20.0	24.0	24.0	24.0	
4 Miniature	10.0		20.0	24.0	24.0	24.0	

1 Model	MOD SG-4 and SH-4	4159.7 hours*
2 Model	MOD SG-7 and SH-7	4016.6 hours*
1 Miniature	MIN 18	661.0 hours*
2 Miniature	MIN 13	669.8 hours*
3 Miniature	MIN 19	651.8 hours*
4 Miniature	MIN 14	707.8 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours test time to June 30, 1961.

Loop Vessel Designation	July						
							1
1 Model							24.0
2 Model							24.0
1 Miniature							24.0
2 Miniature							24.0
3 Miniature							24.0
4 Miniature							24.0
	2	3	4	5	6	7	8
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	24.0	24.0	22.8	24.0	24.0
2 Miniature	24.0	24.0	24.0	24.0	22.8	24.0	24.0
3 Miniature	0.0	24.0	24.0	24.0	22.8	24.0	24.0
4 Miniature	24.0	24.0	24.0	24.0	22.8	24.0	24.0
	9	10	11	12	13	14	15
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	24.0	22.0	24.0	24.0	24.0
2 Miniature	24.0	24.0	24.0	21.5	24.0	24.0	24.0
3 Miniature	24.0	24.0	24.0	20.2	24.0	24.0	24.0
4 Miniature	24.0	24.0	24.0	22.0	24.0	24.0	24.0
	16	17	18	19	20	21	22
1 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
2 Model	24.0	24.0	24.0	24.0	24.0	24.0	24.0
1 Miniature	24.0	24.0	21.7	24.0	22.2	24.0	24.0
2 Miniature	24.0	24.0	21.7	24.0	22.3	24.0	24.0
3 Miniature	24.0	24.0	21.7	24.0	22.3	24.0	24.0
4 Miniature	24.0	24.0	21.7	24.0	22.3	24.0	24.0
	23	24	25	26	27	28	29
1 Model	24.0	12.0	22.7	24.0	24.0	24.0	24.0
2 Model	24.0	12.0	22.4	24.0	24.0	24.0	24.0
1 Miniature	24.0	12.0	22.7	24.0	24.0	24.0	24.0
2 Miniature	24.0	12.0	22.7	24.0	24.0	24.0	24.0
3 Miniature	24.0	12.0	22.7	24.0	24.0	24.0	24.0
4 Miniature	24.0	12.0	22.7	17.3	17.5	24.0	24.0
	30	31					
1 Model	24.0	24.0					
2 Model	24.0	24.0					
1 Miniature	24.0	24.0					
2 Miniature	24.0	24.0					
3 Miniature	24.0	24.0					
4 Miniature	24.0	24.0					

1 Model	MOD SG-4 and SH-4	4890.4 hours*
2 Model	MOD SG-7 and SH-7	4747.0 hours*
1 Miniature	MIN 18	1384.5 hours*
2 Miniature	MIN 13	1392.8 hours*
3 Miniature	MIN 19	1349.5 hours*
4 Miniature	MIN 14	1418.1 hours*

Times shown are hours of test time on vessel in 24-hour period starting at 8:30 on morning of day for which time is shown.

*Total hours service time on vessels. Test terminated on July 31, 1961.

Martin Marietta Corporation
Nuclear Division, Baltimore, Maryland
ANPP CORROSION PROGRAM
Loop Testing of Inconel, Nickel, Monel and Bimetal Heat Exchangers
MND-E-2681 UNCLASSIFIED
J. McGrew, E. Jules
December, 1961 94 pages
Contract DA-44-009-Eng-3581

This report describes corrosion tests, performed under the Martin-ANPP Corrosion Program, on 12 test vessels. Two sets of model heat exchangers (a set consists of a steam generator and superheater) and eight miniature heat exchangers were tested dynamically in a pressurized water loop. One set of model heat exchangers had bimetal tubes (stainless steel in the primary, carbon steel in the secondary) and the other had Inconel tubes. The set with bimetal tubes was service tested for 4890 hours and that with Inconel tubes was service tested 4747 hours. The secondary environment in the bimetal vessels simulated the SM-1 water conditions while the secondary in the Inconel vessels simulated reactor quality water.

Two of the miniature heat exchangers, MIN 10 and 11, had Inconel tubes, MIN 13 and 14 had Monel tubes, MIN 15 and 16 had bimetal tubes and nickel tubes were used in MIN 18 and 19. The test durations for the miniature heat exchangers, MIN 10, 11, 13, 14, 15, 16, 18 and 19, were 3045, 3024, 1393, 1418, 3015, 3035, 1385 and 1350 hours, respectively.

The Inconel, nickel and Monel tubing performed well in both reactor grade and high chloride secondary water. Pitting occurred in all three metals but was less prevalent in the Inconel tubing. The Inconel tubing in the model vessels exposed to reactor grade water did not pit.

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The bimetal model vessels, which were tested using reactor grade water, performed far better than similar vessels exposed previously to a high chloride secondary environment. Nevertheless, the degree of pitting which occurred was prohibitive for long-life steam generators.

Tubing in one of the bimetal miniature vessels was defected to expose stainless steel to the high chloride secondary environment. The hypothesis, that the carbon steel provides cathodic protection and prevents stress corrosion cracking of the stainless steel, was supported by the test results; no cracking of the stainless sublayer occurred. However, complete substantiation should be based on further tests.

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